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A Study on Efficient Calculation of Effective Reactive Power Reserves Using Sensitivity Analysis

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Abstract – In recent academic and industrial circles of the Republic of Korea, the securement of available reactive power reserve against the line faults is at issue. Thus, simulations have been performed for the securing of effective reactive power reserve (effective Q) to prepare for the line faults and improve reactive power monitoring and control methods. That is, a research has been conducted for the fast-decoupled Newton-Raphson method. In this study, a method that distinguishes source and sink regions to carry out faster provision of information in the event of line fault has been proposed. This method can perform quantification with the formula that calculates voltage variations in the line flow. The line flow and voltage changes can be easily induced by the power flow calculation performed every second in the operation system. It is expected that the proposed method will be able to contribute to securement of power system stability by securing efficient reactive power. Also, the proposed method will be able to contribute to prepare against contingencies effectively. It is not easy to prepare quickly for the situation where voltage drops rapidly due to the exhaustion of reactive power source by observing voltage information only. This paper's simulation was performed on the large scale Korean power system in steady state.

Keywords: Power system monitoring, Reactive power reserve, Reactive power sensitivity, Line flow sensitivity, Voltage collapse

1. Introduction

Since the start of electric power industry and to this day, power demands has rapidly increased along with the development of modern technological development, as well as the technologies for the power industry. However, the actual situation in the power industry is that their power systems are operating at the limit of guaranteed stability due to the heavy load as the result of continuous increase in power load. Moreover, the expansion of a large-scale power plant and transmission lines are becoming more difficult because of current social egotism like the NIMBY syndrome so that the long distance power transmission has become an unavoidable reality and this problem is common in many other countries.

Likewise, the electric power supply system in the Republic of Korea is also approaching such a limit due to the same reasons. Especially, on the 15th of September 2011, a nationwide rolling black-outs was executed due to the shortage of generator reserves even there weren't any system disturbances.

Although reactive power plays an important role in maintaining the stability of voltages in the power system and nationwide power interchange, its systematic maintenance and management are not being achieved yet because of society's lack of interest compared to active power and varying regional characteristics. On the other hand, active power has been carefully planned and managed through periodical supply and demand plans and operational standard of reserve powers established by the market participants including government agencies. Since reliable supply of reactive power must be guaranteed to improve the stability of voltages, a precise calculation of reactive power reserve is required. Thus, an improved generator reactive power monitoring and control method has been proposed by performing simulations for the effective reactive power reserve and analyzing the reactive power sensitivity.

A basic research that proposed the reactive power reserve index based on the reactive power margins before and after the accident was performed [1]. Here, a concept that the amount of reactive power reserve becomes 0 when the system approaches near its load-ability limit was presented by applying the simulation technique for Quasi-Steady-State (QSS) to the Nordic 32 test system.

In [2], the authors defined the generator reactive power reserve from a variety of perspectives such as generator supply curve, low-voltage limit and voltage collapse point of PV curve. Here, to calculate a real time voltage instability index, the correlation between the PV margin and the margin of reactive power of each generator was represented with a cubic relation by using the least square method where the Euclidian norm has been applied.

A theory was suggested that the system becomes more

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unstable as the number of generators that have their limits in the reactive power output at the vertex of a PV curve when there a serious accident has occurred [3].

In [4], the authors proposed the VSI when they applied a hierarchical voltage control system to the Italian system. VSI is an index where an increment obtained through adding a differentiated increment to the current generator reactive power output and focuses on how fast each generator's reactive power output changes compared to current change.

According to the current definition of Momentary Reactive Reserve, it refers to the remainder of the calculation where current operational demands has been subtracted from the volume of reactive power source. The Korea Power exchange actually decides the limit of reserves when they review their system. and this limit is updated when they review the peak load operation plan every year [5].

Currently, the majority of power system operators around the world are conducting the voltage stability monitoring task with only such a voltage monitoring method. However, the information from this task alone is not enough as the voltage would not change much even if the reactive power load increases where there is another available reactive power source nearby. The voltage will rapidly drop when available reactive power source has been exhausted so that it is difficult to determine the danger in the stability precisely. On the other hand, the operators obtain quantified reactive power reserve information including the voltage fluctuations with the theory proposed in this study.

In the postulated system accident scenario, an exact and adequate follow up is very important. If voltage limit violation or line overload continue, additional trouble can occur. Thus, the provision of information is essential for prompt and precise actions. The system operators will be able to identify the region deeply affected by the accident if the method proposed here is used. This method will be able to perform calculations for the effective reactive power reserve information to provide it to the operators.

The Fast-decoupled method has been applied to the proposed method. A rapid B matrix-based calculation is possible by using the fast-decoupled method. As the B matrix is constructed based on the power system network topology, calculation is possible without voltage information. All it needs to do is applying the network changes following the postulated accident.

2. The Calculation of Effective Reactive Power Reserves

Generators are a source of reactive power that has fast response characteristics and large capacity [6-9]. Therefore, when calculating reactive power reserves, generators should be considered first. This section deals with the generator's effective reactive power reserves using reactive power sensitivity between generators and load buses. In addition, the calculation method of influential effective reactive power reserves against contingencies is addressed.

$$CQR = \sum_{i=1}^{n} Q_{CQR}^{i} = \sum_{i=1}^{n} (Q_{\max}^{i} - Q_{gen}^{i}) \tag{1}$$

Where, n is the total number of generators, Q^i_{CQR} is the reactive power reserve of i-th generator, Q^i_{max} is the rated maximum reactive power output of i-th generator, and Q^i_{gen} is the current reactive power output of i-th generator.

Reactive power has local characteristics which differ from that of frequency, so all generators are not affected equally in a power system [10-13]. CQR (Conventional Reactive Power Reserve) is a simple sum of a generator's output that does not reflect the characteristics of the generator and appears larger than actual reactive power reserves. Therefore, when a system collapse situation arises due to a lack of reactive power, actual reactive power reserves do not exist, but CQR shows that reactive power reserves remain. For this reason, CQR cannot provide accurate information to the user which can lead to a failure to respond to contingencies [6-9]. Therefore, a method of calculating accurate reactive power reserves that considers the local characteristics of reactive power and system changes is necessary.

EQR (Effective Reactive Power Reserve) is the quantified value of the differential effect to the system using linear sensitivity that reflects the electric characteristics of generators [10]. EQR is defined as the value obtained from multiplying CQR by a weight factor which considers the rated output of each generator. Calculating the EQR is necessary for calculating accurate reactive power reserves during system collapse situations.

Calculating sensitivity between the load and generator is the first step of calculating EQR and is done by using the Jacobian matrix of the power flow equation [2]. Reactive power is related to voltage and active power is related to phase angle, so to represent the change of load for the change of reactive power output can be done using the fast decoupled method [8].

The fast decoupled power equation can be represented as a relational expression between generators and loads [4].

$$\begin{aligned} \Delta Q_G &= -[B_{GG}]\cdot \Delta V_G - [B_{GL}]\cdot \Delta V_L \\ \Delta Q_L &= -[B_{LG}]\cdot \Delta V_G - [B_{LL}]\cdot \Delta V_L \end{aligned} \tag{2}$$

Where, B_{GG} is the B matrix of the generator-generator cells, B_{GL} is the B matrix of the generator-load cells, B_{LG} is the B matrix of load-generator cells and B_{LL} is the B matrix of the load-load cells.

Reconstruct the above equations in terms of voltage as:

$$\begin{aligned} \Delta V_L &= -[S_{LG}][\Delta Q_G] + [S_{LL}][\Delta Q_L] \\ \Delta V_G &= -[S_{GG}][\Delta Q_G] + [S_{LG}]^T[\Delta Q_L] \end{aligned} \tag{3}$$

$$\begin{aligned} S_{GG} &= \{[B_{GG}]-[B_{GL}][B_{LL}]^{-1}[B_{LG}]\}^{-1} \\ S_{LG} &= [B_{LL}]^{-1}[B_{LG}][S_{GG}] \\ S_{LL} &= -[B_{LL}]^{-1}-[S_{LG}][B_{GL}][B_{LL}]^{-1} \end{aligned} \tag{4}$$

If it is assumed that the terminal voltage does not change during normal conditions, the above equation can be represented as the change of generator reactive power output over the change of load bus reactive power, as follows [4]:

$$\frac{\Delta Q_G}{\Delta Q_L} = [S_{GG}]^{-1}[S_{GL}] \tag{5}$$

Therefore, $[S_{GG}]^{-1}[S_{GL}]$ represents the value that is the generator reactive power change over load bus reactive power change. This is the normalization value for quantifying the effects of other generators to the system when it is assumed that the system contribution rate of generator which has the largest sensitivity value is 100%.

The normalization process proceeds as follows. Apply the maximum norm which divides sensitivity of the other generators by sensitivity of the generator that has the largest sensitivity. Represent this as follows [5]:

$$\begin{aligned} In &= Norm[\{x,y\}, Max(x,y)] \\ Out &= \left\{ \frac{x}{Max(x,y)}, \frac{y}{Max(x,y)} \right\} \end{aligned} \tag{6}$$

The new sensitivity equation that is calculated by normalization results in the weight factor of each generator. At this time, the standard of normalization is the maximum sensitivity between generators and the monitoring bus, because the EQR the on monitoring bus can be calculated when it is normalized by using sensitivity between the monitoring bus and generators.

EQR is calculated by multiplying the CQR by the weight factor that is defined above [5].

$$\text{EQR} = \sum_{i=1}^{n} \lambda_i \cdot Q^i_{CQR} = \sum_{i=1}^{n} \lambda_i \cdot \left(Q^i_{max} - Q^i_{gen} \right) \tag{7}$$

Where, n is the total number of generators, Q^i_{CQR} is the reactive power reserve of the i-th generator according to CQR, Q^i_{max} is maximum output of the i-th generator, Q^i_{gen} is current output of the i-th generator, and λ_i is weight factor of the i-th generator.

Conventional EQR sets the voltage control area in a system based on the sensitivity information, chooses the pilot bus and participation generators in each voltage control area, and calculate the EQR by each area. This method has the problem of difficulties in considering the reactive power effect from the adjacent area to the voltage control area. Therefore, an advanced method of calculating EQR is necessary to consider not only local characteristics of reactive power but also the effects of the adjacent area [14-15].

This paper proposes a method of calculating contingency-based EQR on the entire system and generators, except for choosing voltage control area and participation generators.

3. The Application Method of EQR against Contingencies

Securing proper reactive power reserves is very important to prevent system collapse. To secure proper reactive power reserves, an accurate calculation of reactive power reserves should be done that can thoroughly consider the seriousness of the contingency. This section deals with calculating the contingency-based EQR by choosing the monitoring bus considering contingencies and power flow.

3.1 Select the monitoring bus by considering the voltage sensitivity of power flow

The conventional EQR method proposes the calculation of reactive power reserves at the monitoring bus that is chosen by using the reactive power sensitivity in the network, so it is representative of the immediate area, but cannot react well to reactive power change of the bus that has a long distance from the monitoring bus. Additionally, the conventional EQR method doesn't consider the effects of contingencies because the monitoring bus is chosen only based on sensitivity. Because of these weaknesses, the conventional EQR method is not optimal for a reactive power monitoring index when contingencies have occurred. Therefore, it is important to select a monitoring bus which considers the contingency when calculating the useful EQR.

Also, to select the monitoring bus by considering the direction of the power flow is effective for determining the weakness of reactive power in the system.

If reactive power flow is transmitted to B from A by the transmission line between A and B, such as in Fig. 1, A is classified as a source area and B is classified as a sink area. When contingencies have occurred in the transmission line between A and B, then reactive power flow between A and B goes to B by bypass lines. Therefore, reactive power reserve at B (sink area) is reduced more than A (source area). It is described in Fig. 2.

This result reveals that the reactive power reserve of the sink area is more affected by adjacent contingencies than

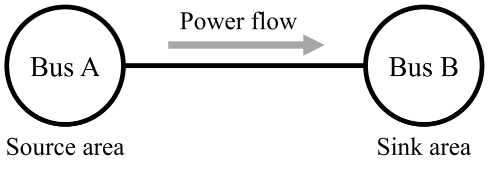

Fig. 1. The power flow between two buses

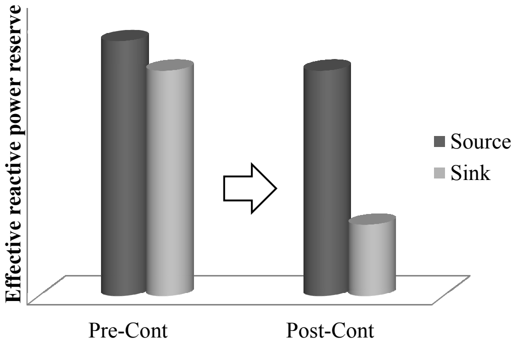

Fig. 2. The EQR change of source and sink area after contingency

reactive power reserves of the source area [16-17]. Furthermore, the reactive power reserves of the sink area are smaller than the source area when contingencies have occurred. For this reason, the sensitivity of power flow has to be considered.

If the directions both active power and reactive power flows are the same, the source and sink regions can be distinguished intuitively. However, if the directions are different, it is difficult to make a judgment on which end of main line has been affected by the line fault. Generally, reactive power affects the level of voltage more. Nevertheless, if the level of active power is higher, it will have more influence so that it is necessary to quantify the influence when distinguishing the source and sink regions. Therefore, the voltage change sensitivity in main line measured against the change in line flow was calculated in this study as following:

$$\frac{\partial V_m}{\partial f_{ij}} = \sum_{k=1}^{n}\left(\frac{\partial V_m}{\partial P_k}\frac{\partial P_k}{\partial f_{ij}} + \frac{\partial V_m}{\partial Q_k}\frac{\partial Q_k}{\partial f_{ij}}\right) \tag{8}$$

V_m is the voltage at the bus m. f_{ij} is the branch flow (MVA) on branch form bus i to j.

The voltage change in mainline in the event of postulated accident of Line i-j can be calculated as:

$$\Delta V_m = \frac{dV_m}{df_{ij}}\Delta f_{ij} \tag{9}$$

Δf_{ij} is the branch flow change by a contingency at line i-j. The main line with the larger voltage change is distinguished as sink region.

3.2 Algorithm of the contingency-based EQR application method

For preparing contingencies, it is important to quickly calculate EQR. Selecting the monitoring bus by considering the contingency area and power flow is important for fast contingency-based EQR calculations. These are applied to the algorithm in Fig. 3.

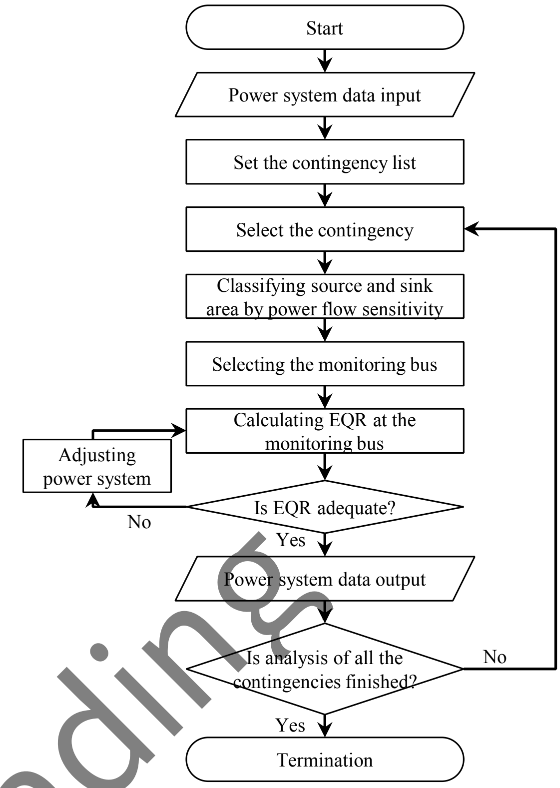

Fig. 3. Algorithm of the contingency-based EQR application method

Fig. 3 shows an algorithm for securing the appropriate reactive power reserve in the power system in real time. First, load power system data. Next, the contingency list set by the power system operator is read and simulate contingencies for the power system. Based on the power flow sensitivity value at the contingency, divide the sink and source areas. Then, it is possible to quickly calculate the EQR in the sink area. If the calculated EQR value is smaller than the EQR limit set by the power system operator, the power system adjustment is performed to satisfy the EQR limit. As a result of performing this algorithm, it is possible to confirm the available reactive power reserve in the power system and to prepare necessary action to secure an adequate reactive power reserve in the contingency situations.

4. Performance Evaluation

This section shows the simulation result of applying the proposed method to the Korea power system. Reactive power reserve was calculated for major contingency cases and verified. Fig. 4 shows the main part of Korea power system. Korea power system of the studied scenario is operating with total reactive power load demand of 28573.74 Mvar, 1299 Buses, 2012 Branches and 335 Generators.

The previously study on EQR selected DongSeoul as the

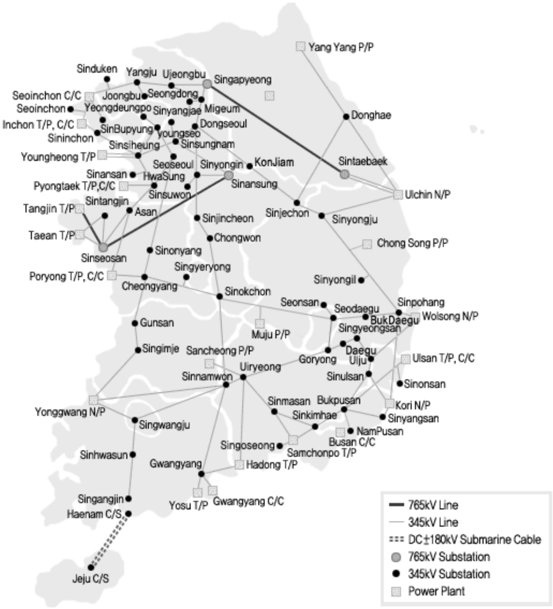

Fig. 4. Organization of Korea power system

Table 1. EQR change at DongSeoul by contingencies

No	Contingency	EQR [Mvar]	Rate of EQR change
	No contingency	4364	-
1	Gwangyang3-YeosuTP3	4334	-0.69%
2	SinSiheung3-SinIncheon3/ SinIncheon3S	3968	-9.07%
3	SinPaju3S-SeoIncheonC3	3875	-11.21%
4	SinPaju3S-Yangju3	3871	-11.30%

Table 2. Power flows between source and sink areas

No	Source	Sink	Flow[MVA]
1	Gwangyang3	YeosuTP3	668+j205
2	SinSiheung3	SinIncheon3	122+j52
3	SeoIncheonC3	SinPaju3S	1342+j137
4	SinPaju3S	Yangju3	1334+j2

particular bus [5]. The reason is that DongSeoul is more sensitive to control generators than other buses. But as the contingency area is far from DongSeoul, the impact from the contingency is low. Therefore, the EQR of DongSeoul can't accurately reflect the impact of contingency. Table 1 shows the EQR change at DongSeoul by major contingencies. EQR changes of Gwangyang3-YeosuTP3 case is the smallest change in the above results. It shows that DongSeoul3 wasn't affected by Gwangyang3-YeosuTP3 contingency.

This is because Gwangyang3-YeosuTP3 line is farther than other lines from DongSeoul. This result shows that the particular bus based on sensitivity can't accurately reflect the effect of the line distance. Therefore, it is important to select the monitoring bus by reflecting the impact from contingencies. For this, we selected buses on both sides of the contingency lines. Next, we sort each of the two buses into source area and sink area based on power flow sensitivities. Table 2 shows power flows between source and sink areas. The power flow amount is based on the source area.

The predicted voltage change values corresponding to the flow sensitivities and contingencies calculated through Eq. (14) and (15) are shown in the Table 3.

It is possible to confirm that the values are much larger in the sink region. This means that there will be a problem in demand and supply of reactive power in the sink region in the event of line fault. To confirm this, the changes in EQR in both regions were checked. Then, we compared EQR at the source area and the sink area. The following results in Table 4, Fig. 5 and Fig. 6 are EQR values on both sides of each line when a line contingency has occurred.

The simulation results showed that there were not much changes in the effective reactive power reserve in source region but the same had been largely reduced after the accident. Such a result confirms that the supply and demand of reactive power has been affected by the severed line which used to supply reactive powers in the sink region.

In the Table and Figures, the rate of EQR change at the source area is smaller than the sink area. At Gwangyang3-

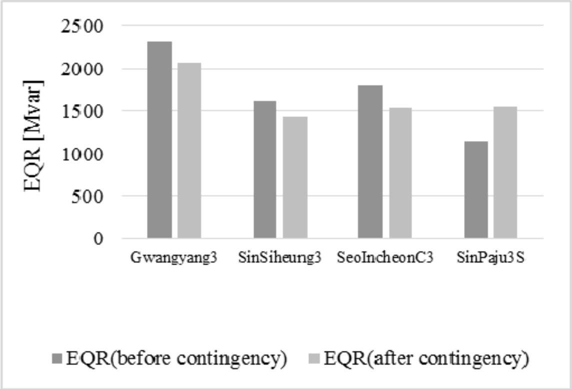

Fig. 5. EQR changes at source areas after contingencies

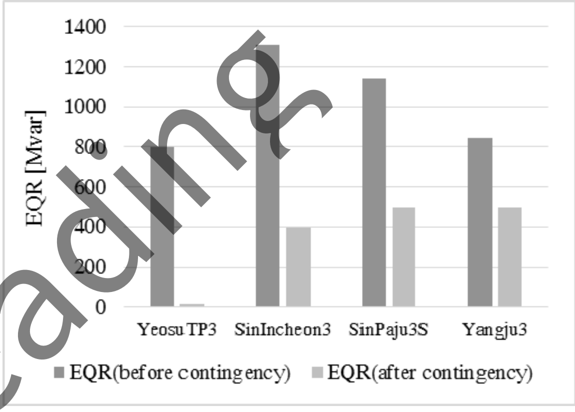

Fig. 6. EQR changes at sink areas after contingencies

Table 3. Power flow sensitivities between source and sink

No	Source	Voltage/flow sens.	ΔV	Sink	Voltage/flow sens.	ΔV
1	Gwangyang3	-0.0001	-0.0007	YeosuTP3	-0.00281	-0.0197
2	SinSiheung3	-0.0014	-0.0009	SinIncheon3	-0.0022	-0.0037
3	SeoIncheonC3	-0.0001	-0.0013	SinPaju3S	-0.0007	-0.0099
4	SinPaju3S	-0.0002	-0.0020	Yangju3	-0.0003	-0.0041

Table 4. EQR at source and sink areas after contingencies

No	Contingency list	Monitoring Bus	Before Cont. EQR [Mvar]	After Cont. EQR [Mvar]	Rate of change
1	Gwangyang3 - YeosuTP3	Gwangyang3 (source)	2326	2071	-11%
		YeosuTP3 (sink)	802	14	-98%
2	SinSiheung3 - SinIncheon3 /SinIncheon3S	SinSiheung3 (source)	1609	1429	-11%
		SinIncheon3 (sink)	1309	396	-70%
3	SinPaju3S - SeoIncheonC3	SeoIncheonC3 (source)	1801	1535	-15%
		SinPaju3S (sink)	1143	498	-56%
4	SinPaju3S - Yangju3	SinPaju3S (source)	1143	1552	36%
		Yangju3 (sink)	845	495	-41%

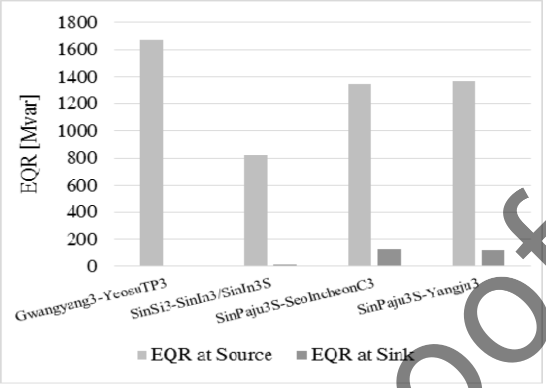

Fig. 7. EQR at voltage collapse point

YeosuTP3 contingency, EQR Gwangyang3 (source area) changed -11% and EQR at YeosuTP3 (sink area) changed -98% after contingency. It shows that Gwangyang3-YeosuTP3 contingency is very critical. This is because the EQR of YeosuTP3 shows that YeosuTP3 doesn't have enough reactive power reserves. At SinPaju3-SinIncheon C3/ SeoIncheonC3 contingency, EQR at SeoIncheonC3 (source area) changed -24% and EQR at SinPaju3 (sink area) changed -76% after contingency. At SinSiheung3-SinIncheon3/SinIncheon3S contingency, EQR at SinSiheung3 (source area) changed -11% and EQR at SinIncheon3 (sink area) changed -70% after contingency. At SinPaju3-Yangju3 contingency, EQR at SinPaju3 (source area) changed 34% and EQR at Yangju3 (sink area) changed -45% after contingency. These results show that the EQR at the sink area is more affected than the source area by contingency. Therefore, the bus of a sink area near the contingency has to be selected as the monitoring bus for observing the risk of contingency.

Next, for verification of EQR effectiveness, we increased reactive power load close to the contingency area and made a condition at the critical operation point.

Table 5. EQR at voltage collapse point

No	Contingency	Monitoring bus	Load increase [Mvar]	EQR [Mvar]
1	Gwangyang3 - YeosuTP3	Gwangyang3	0	2071
			190	1670
		YeosuTP3	0	14
			190	0
2	SinSiheung3 - SinIncheon3/ SinIncheon3S	SinSiheung3	0	1429
			3470	820
		SinIncheon3	0	200
			3470	16
3	SinPaju3S - SeoIncheonC3	SeoIncheonC3	0	1535
			1030	1352
		SinPaju3S	0	498
			1030	125
4	SinPaju3S - Yangju3	SinPaju3S	0	1552
			980	1371
		Yangju3	0	495
			980	117

The following results of Table 5 and Fig. 7 shows EQR at the critical operation point of each case. In the results of Table 5 and Fig. 7, the EQR at sink area is very small compared to other areas at the critical operation point. These results show the effectiveness of EQR about the severity of contingency. The results show that the EQR is sufficient in the source regions, but lacks the EQR in the sink regions at voltage collapse point.

5. Conclusion

This paper proposes the application of effective reactive power reserves (EQR) against contingencies. The weakness of existing EQR studies is that EQR couldn't reflect the impact of contingencies that are distant from the monitoring bus. This is because the monitoring bus was only selected as the most sensitive bus of network. Therefore, this paper proposes the method to select the monitoring bus for the application method of EQR against contingencies.

When a contingency occurs, in general, the reactive power output of generators increases and thus the reactive power reserve of generators decreases. This is because the impedance of network is increased and thus the reactive power loss is increased. However, the change in quantity of each generator output is different. A sensitive generator for a contingency generates more reactive power than an insensitive generator. Therefore, it is important to calculate the EQR at a bus near the contingency line. Additionally, it is also important to consider the previous power flow of a contingency at a contingency line. A bus receiving power from a contingency line has a problem whenever a line contingency occurs. We classified both end buses of a contingency line in the Korea power system. The bus receiving power is classified as a sink area and the bus sending power as a source area. Also, we verified that the EQR of a sink area is significantly decreased when a contingency occurs. Therefore, it is important to select the sink area as the monitoring bus. Then, we checked the EQR of the sink area at the critical operation point and verified its effectiveness.

In future research, a study about increasing accuracy of EQR will be performed by using nonlinear sensitivity equations.

Acknowledgements

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