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A Study on the Multiple FACTS Control for Ensuring the Voltage Stability in Jeju Island System

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Abstract – Voltage instability results from a lack of reactive power support in a power system. One effective solution for supplying reactive power to a power system is utilization of flexible alternating-current transmission system (FACTS) facilities. Currently, two FACTS facilities are operated for stable operation of the power system on Jeju Island in South Korea. Both FACTS respond to disturbances to stabilize voltage fluctuations in the island power system, however there is potential for mutual interference between them because they are operated using measured voltage without a coherent system operation strategy; cooperative control between the two would result in more effective system operation. Here, a multiple FACTS control algorithm is developed for effective operation of the island power system. The algorithm is based on two methods: calculation of the effective reactive power (Q) reserve (EQR) to obtain an accurate reactive power for the system, and GV analysis to account for the two HVDC interconnections between Jeju Island and the Korean Peninsula.

Keywords: Multi-FACTS, Reactive power compensation, Voltage stability, Effective reactive power (Q) reserve (EQR), Sensitivity analysis, GV analysis

1. Introduction

Voltage is a key factor in power system operation [1, 2]. Voltage is related to reactive power, so any analysis of voltage stability should consider reactive power supply facilities such as generators, capacitors, and flexible alternating-current transmission systems (FACTS) [3]. To control a bus voltage, reactive power supply facilities should be located near the bus because reactive power cannot be transmitted across long distances [4]. Therefore, selection of a reactive power source and its coordinated control are necessary to control the voltage in a power system. The use of FACTS facilities is a particularly effective method for controlling voltage, and several studies have investigated such systems [5-7]. In this paper, a multiple FACTS control algorithm for an island power system is proposed for stable operation, with Jeju Island selected as the test bed. The Jeju Island power system has unique electrical framework characteristics, as it incorporates various voltage control facilities and two FACTS.

Currently, Jeju Island receives 40% of its power from the mainland through a high-voltage direct current (HVDC) line. Another HVDC line was initially test-operated, and since 2014 HVDC lines #1 and #2 have operated together to supply Jeju Island with electricity from the mainland. HVDC #1 and #2 are both line-commutated converter (LCC HVDC) lines, and are installed along with a harmonic filter and a number of reactive power sources [8]. As shown in Fig. 1, HVDC #1 is installed between Jeju and Haenam and HVDC #2 is installed between Jin Island and West Jeju.

The proportion of power being supplied from the mainland through the HVDC lines is expected to increase considerably due to the operation of HVDC #2. The penetration of wind power will also increase, thereby requiring a suitable combination of HVDC transmission, wind generation, and conventional power plants in the Jeju system. HVDC #1 presently operates at a capacity of 150 MW, and during concurrent operation with HVDC #2,

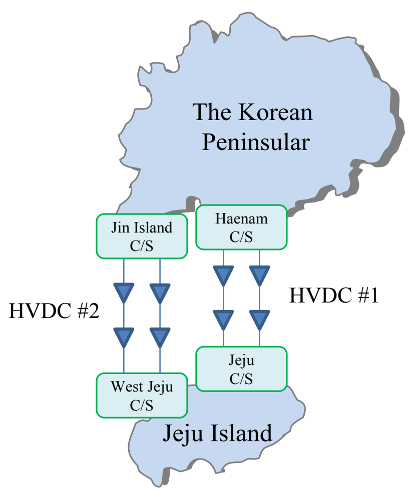

Fig. 1. HVDC interconnection between the Korean Peninsula and Jeju Island

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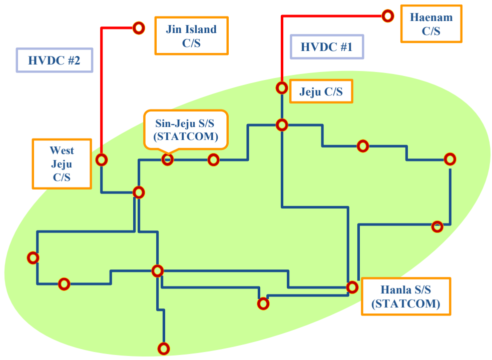

Fig. 2. The location of the two FACTS on Jeju Island

HVDC #1 and HVDC #2 will operate at maximum powers of 300 MW and 400 MW and operating capacities of 150 MW and 200 MW, respectively. The maximum load of the island in 2014 was 730 MW [9]. Two FACTS are operated to improve voltage stability on Jeju Island; both are static synchronous compensators (STATCOMs) and have the same capacity, 50 MVar. A STATCOM has the ability to act as either a source or a sink of reactive power to the power system, with a very fast response time.

Voltage stability is strongly affected by reactive power control due to the local characteristics of reactive power [10]. As shown in Fig. 1, the two STATCOM units are installed at some distance from one another and have different ranges of influence. If reactive power control becomes necessary to cope with a disturbance in the Jeju power system, a methodical STATCOM control strategy that considers the location of any disturbance should be implemented to rectify voltage instability and maintain the system. In this paper, an algorithm is developed for a coordinated FACTS control method.

Consideration of reactive power-supply facilities is necessary for coordinated control. On Jeju Island, HVDC lines, FACTS, and wind farms should all be considered to control reactive power. In this paper, the algorithm developed is based on two methods that consider the effect of reactive power supply facilities. First, the EQR concept is used to calculate an accurate reactive power margin. The EQR gives the margin for the current power system situation and is described in detail in Section 2. Second, the GV analysis method is used to reflect the unique characteristics of the Jeju power system. GV analysis can be used to obtain an index that accounts for HVDC transmission and frequency control. The concept of GV analysis and its importance in the algorithm are described in Section 3. In Section 4, the multiple FACTS control algorithm is presented, and case studies are described in Section 5. Conclusions and comments are presented in Section 6.

2. Definitions of Effective Reactive Power Reserve

In this paper, the concept of an effective reactive power reserve, the EQR, is used for multiple FACTS control. To describe the concept of the EQR, the difference between the EQR and the constant reactive power reserve (CQR), commonly used in power flow calculations, should be explained. Every generator has the ability to supply reactive power, with a maximum and minimum limit of reactive power from each machine. The maximum value remains constant during power flow, and the generator reactive power reserve is defined as:

$$Q^i_{\mathrm{CQR}} = Q^i_{\max} - Q^i_{\mathrm{gen}} \tag{1}$$

where Q^i_{CQR} is the reactive power reserve of the i th generator with respect to the CQR; $Q^i_{\max}$ is the maximum reactive power of the i th generator; Q^i_{gen} is the current reactive power dispatched by the i th generator.

If we consider the point of collapse as the limit, the amount of reactive power reserve can also be defined as follows [11]:

$$Q^i_{\mathrm{VQR}} = Q^i_{\mathrm{vcol}} - Q^i_{\mathrm{gen}} \tag{2}$$

where Q^i_{VQR} is the reactive power reserve of the *i* th generator with respect to voltage collapse; Q^i_{vcol} is the maximum reactive power of the i th generator at the point of voltage collapse.

When a disturbance occurs in a power system, some generators are able to affect the disturbance while others cannot, because long-distance transmission of reactive power is not possible. Thus, selection of important generators is necessary for accurate calculation of the reactive power reserve. Considering these factors, the EQR can be calculated as:

$$Q^i_{\mathrm{EQR}} = \lambda_i \cdot Q^i_{\mathrm{CQR}} \tag{3}$$

where Q^i_{EQR} is the reactive power reserve of the *i* th generator with respect to the EQR; λ_i is the weighting factor of the i th generator.

The system EQR is defined as the sum of all generator EQRs, and, similarly, the system CQR is defined as the sum of all generator CQRs. It is possible to get CQR from general power flow calculations and EQR means the

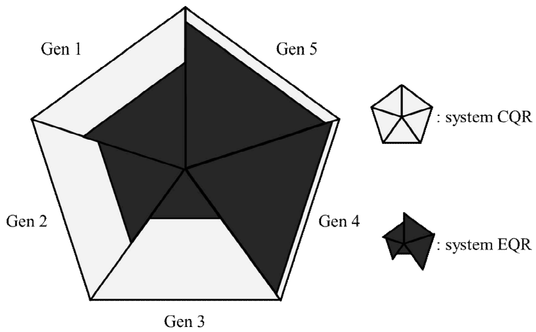

Fig. 3. EQR concept diagram

realistic sum of reactive power considering reactive power loss in transmission (or distribution) lines. It can be seen from (3) that the EQR is sensitive to network and load characteristics. In other words, when a severe disturbance occurs in the power system, the EQR is computed based on the sensitivity of each generator with respect to a particular bus. The concept of the EQR and the algorithm for calculating the EQR are described in detail in [12].

3. GV Analysis

The HVDC lines perform frequency control in the Jeju power system. When there is frequency fluctuation, an HVDC line responds before the generators react, and maintains the frequency at 60 Hz. When there is some disturbance that would result in a shortage of active power in the Jeju power system, the HVDC line that is under frequency control quickly increases the amount of active power transmission. The reactive power, which is around 65% of the active power, is absorbed by the HVDC line. This increase in the active power and the absorption of reactive power is achieved rapidly. If the required reactive power for HVDC operation is insufficient, the Jeju power system will collapse under the disruption of the reactive power balance.

The GV index is necessary for an analysis of the particular characteristics of the Jeju power system. If the power system is not in the steady state by the time of the disturbance, it is not possible to perform a power system analysis using a general power flow calculation method. Jeju power system shows the particular characteristics so general analysis method is not valid for this system. In order to solve this problem, GV (generation-voltage) analysis using continuous power flow calculation has been developed for analysis of Jeju power system [13]. Using GV analysis, the power flow calculation can be converged under abnormal conditions. The power system disruption point can be calculated using GV analysis after a disturbance, and sensitivity data acquisition is possible using that point. The sensitivity data are used to operate system control facilities such as a STATCOM. In GV analysis, a continuous power flow calculation is carried out with a variation in parameters (mainly generator outputs). In [14], a continuous power flow calculation method that uses generator outputs as parameters is described, and defined as the generation continuation power flow (GCPF). This GCPF is used for GV analysis, requiring models of some system components including contingency generators and HVDC lines. The contingency generator is defined as the ‘tripping generator’ and may be described mathematically as follows:

$$P_{Gi}(\lambda) = (1-\lambda)\times P_{G0i} \tag{4}$$

$$Q_{Gi\_MAX}(\lambda) = (1-\lambda)\times Q_{Gi\_MAX0} \tag{5}$$

$$Q_{Gi\_MIN}(\lambda) = (1-\lambda)\times Q_{Gi\_MIN0} \tag{6}$$

where P_{Gi} and P_{G0i} denote the active power output of the i-th generator during and before the incident, respectively, λ denotes the stress parameter in the power system, Q_{GI_MAX} and Q_{GI_MAX0} denote the maximum limits of the reactive power output of the i-th generator during and before the incident, respectively, and, likewise, Q_{GI_MIN} and Q_{GI_MIN0} denote the minimum limits of the reactive power output of the i-th generator during and before the incident, respectively.

The HVDC model can be expressed using the active (P) and reactive (Q) power loads [15]:

$$P_{HVDC}(\lambda) = -(P_{HVDC0} + \lambda P_{G0}) \tag{7}$$

$$Q_{HVDC} = \alpha \times P_{HVDC}(\lambda) \tag{8}$$

In (7), P_{HVDC} denotes the amount of electricity transmission through the HVDC lines and can be regarded as a negative load within the framework of the Jeju power system. P_{HVDC0} and λ_{PG0} denote the amount of transmission before the incident, and a parameterized figure of the output variation of the contingency generator, respectively. A CSC HVDC line has a reactive power absorption characteristic in proportion to the amount of real power flow in transmission; it is therefore possible to model CSC HVDC power as a positive Q load. In (8), Q_{HVDC} denotes the amount of reactive power absorption and α is the Q/P ratio in the CSC HVDC lines.

GV analysis is a method of analyzing power-system stability and active power margins. In GV analysis, the “contingency generator” means that an incident occurs in that generator. The analysis is performed by increasing HVDC transmission of active power by the same amount as the reduced output of the contingency generator. Fig. 4 shows the concept of GV analysis, and the horizontal axis shows the increasing HVDC transmission of active power considering the decreased power of the contingency generator.

Assuming the output of the contingency generator was P_0 in the pre-contingency state, the point P_0 on the x-axis of Fig. 4 denotes a viable operating point in the post-contingency state. In other words, the HVDC transmission here is increased by the output of the contingency

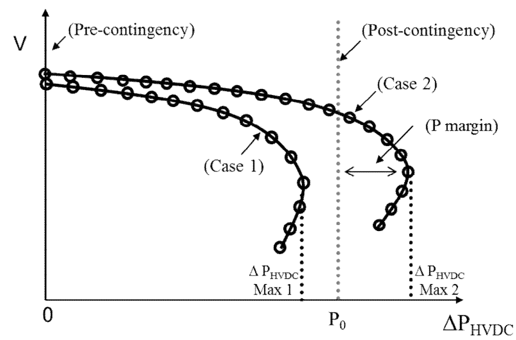

Fig. 4. Examples of GV curves

generator before the contingency. As discussed earlier, reactive power absorption increases in proportion to the increase in active power flow in a CSC HVDC line. As the x-axis value (ΔP_{HVDC}) in Fig. 4 increases, the reactive power margin and bus voltage decrease in the power system. If there is insufficient reactive power in the power system, a limiting point is reached. The maximum shifting capacity from the contingency generator to an HVDC line, considering stability in terms of reactive power, is ΔP_{HVDC}_Max. In Fig. 4, curve 1 shows an active power output of the contingency generator greater than ΔP_{HVDC}_Max_1. In this case, because a power-flow solution does not exist, the system is unstable. Curve 2 shows an active power output of the contingency generator smaller than ΔP_{HVDC}_Max_2. In curve 2, the system can be operated stably. Additionally, an active power margin can be calculated using GV analysis for curve 2.

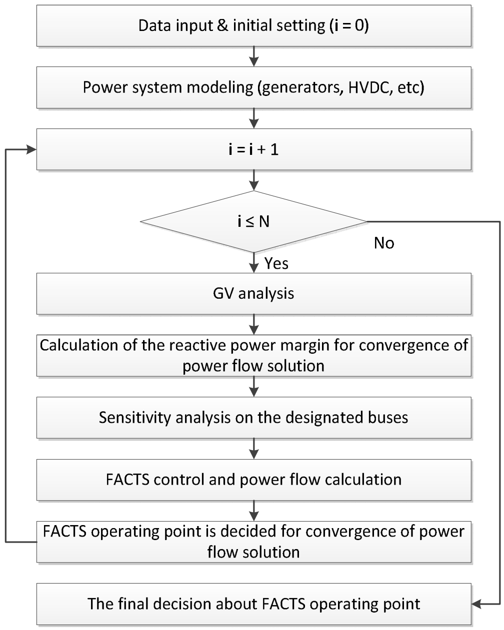

Fig. 5. Control algorithm in GV module

4. Multi-FACTS Coordinated Control Algorithm

4.1 GV analysis module for the algorithm

In this study, a multi-FACTS coordinated control algorithm is proposed for operation of an island power system. There are two FACTS in the Jeju Island power system, and the algorithm is applied to this system. GV analysis is a necessary component of the proposed algorithm, for calculation of a power margin in the island power system. The calculated margin is used to estimate the amount of additional power needed for stable system operation.

Power system data, contingency generator bus data, control parameter data and contingency data are necessary for GV analysis and continuation of power flow. If the system is unstable, an additional reactive power reserve using FACTS can provide a solution. The FACTS control algorithm using GV analysis is described in Fig. 5 and can be detailed as follows.

Data input and initial setting are performed in the first step. The count variable 'i' is set as zero in this step. Modeling of power system components, such as generators or HVDC lines, is performed in step 2. In this algorithm, 'N' means the total number of contingencies that should be considered in the analysis, and each contingency has a unique number. In step 3, the variable i is incremented by 1. If i is greater than N, the process proceeds to the final step. Otherwise, the calculation proceeds to the next step. In step 5, GV analysis is performed considering a contingency. The reactive power margin is calculated in step 6. To calculate the reactive power margin, an additional active power (ΔP) calculation is necessary. The reactive power margin means the amount of reactive power necessary for additional real power transmission in the HVDC lines. In step 7, a sensitivity analysis is performed on the designated buses. The calculated reactive power margin is necessary for this analysis. Vulnerable buses can be obtained from the sensitivity analysis, which is also used for calculation of tangent vectors between vulnerable buses and the FACTS bus. Reflecting the result of that analysis, the reactive power margin can be divided between each FACTS. After renewal of an operating point using the result of the previous step, power flow calculations are performed to verify the result of the algorithm in step 8. An optimal operating point is saved in step 9 and the algorithm then moves to step 3 to analyze the next contingency. If all analyses are completed for every contingency, the algorithm proceeds to step 10. In step 10, the most severe case is selected as the final operating point from the calculated results.

4.2 EQR module

The EQR module forms part of the multi-FACTS control algorithm. Power system data, EQR stability margin criteria, contingency data and parameters for EQR analysis are necessary inputs for the EQR module. The flow chart of the FACTS control algorithm with EQR analysis is shown in Fig. 6.

First, sensitivity analyses are performed using input data between designated buses and the FACTS bus. Next, the EQR analysis is performed and the results of the analysis are checked using the stability criterion. If the results meet the criterion, a FACTS operating point will be obtained from the calculation result. If the result does not meet the criterion, the algorithm proceeds to the next step to calculate Q_{ref} of the FACTS. Q_{ref} denotes a reactive power reference and describes the amount of reactive power required in the FACTS to control the voltage. It is advantageous to secure a reactive power reserve in a vulnerable bus or sensitive (high sensitivity index) FACTS. Next, the power flow calculation is carried out to acquire the V-Q sensitivity (ΔV/ΔQ) and then the terminal voltage is calculated using this V-Q sensitivity. Finally, the FACTS is set up based on these results and returns to the EQR calculation step. Using these procedures, a reasonable operating point for the FACTS can be obtained.

4.3 Coordinated control algorithm

A multiple FACTS coordinated control algorithm is described in this section. The algorithm includes the GV analysis module and the EQR module, and a flow chart of the procedure is presented in Fig. 7. The first step in the algorithm is verification of the input data. A power flow calculation is carried out to verify convergence in the early stage of the algorithm. If the power flow calculation is not converged, this indicates an error in the input data, and the algorithm should be terminated. If convergence is achieved, the original input data (OID) are saved and modified input data (MID) are generated for contingency analysis. Next, the GV margin is calculated in the GV module. If the calculated GV margin is less than 1, the power system may face system collapse from a modest disturbance. To prevent this, it is necessary to secure a sufficient reactive power reserve margin. An operating point has already been decided by this step so analysis using the EQR module is not performed. If the GV margin is greater than 1, the calculation proceeds to the EQR margin calculation step. The calculation and security checking of the GV margin are performed in the GV module, and those of the EQR margin are carried out in the EQR module. After a GV or EQR margin has been secured, an operating point for the FACTS is set up and system stability is checked by contingency analysis considering the new operating point.

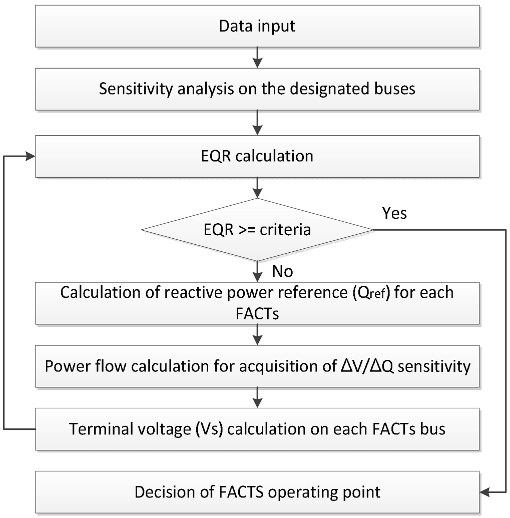

Fig. 6. Data flow in EQR module

5. Case studies

The Jeju Island power system is used as a case study to verify the proposed algorithm because two FACTS facilities are operated in the system. A brief description of the Jeju Island power system has been provided in earlier

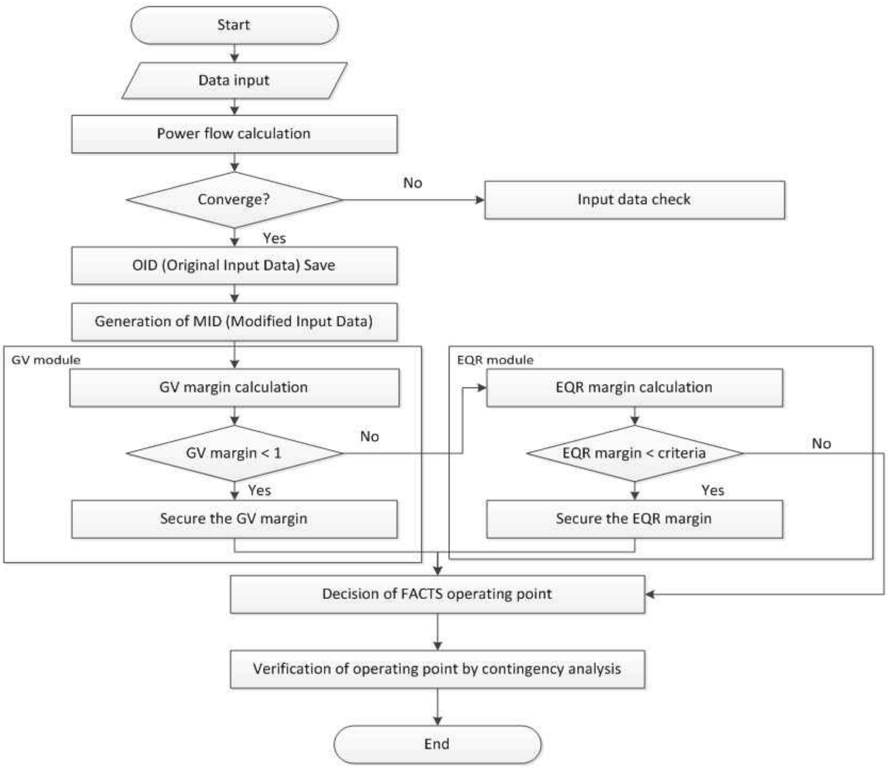

Fig. 7. Final algorithm for operating point decision

sections, and details of the system parameters used in the simulation are shown in Table 1.

5.1 CASE I – Divergence of power flow calculation and GV analysis

In case I, a fault in the Southern Thermal Plant is used as a contingency. The capacity of the generator is 100 MW, a significantly large size on the scale of the whole Jeju island power system. Under heavy load conditions, there is a possibility that the power flow calculation will diverge under that contingency. A power system operating point is not easily obtained using a normal power flow method, so GV analysis is used to analyze this case. The result of the GV analysis is shown in Fig. 8.

Fig. 8 shows that the GV margin is 0.8797 and hence is less than 1.0. According to the algorithm in Fig. 7, this case should move on to the next procedure to secure the GV margin. According to the algorithm in Fig. 5, a sensitivity analysis at the knee point is necessary at this stage. The results of the sensitivity analysis are summarized in Table 2.

The FACTS operating points are changed in response to the sensitivity analysis results in the FACTS control algorithm. The new FACTS operating points are shown in Table 3.

The results shown in Table 3 indicate that the new operating points have more inductive characteristics compared to the initial point. The power system has an adequate reactive power reserve as a result of these actions, and should remain stable during a disturbance. To verify this solution, simulations were performed after the set-up of these new operating points, which showed that the power flow calculation converged under the same conditions (100 MW unit fault). The GV analysis result of the simulation is shown in Fig. 9, which shows that the GV margin is greater than 1 - the maximum value of G was equal to 1.0552 in this case.

Table 1. Overview of the JEJU power system.

System component	Jeju Island power system
P load	682 MW
Q load	214 MVar
# of bus	31
FACTS	Sin-Jeju STATCOM (50MVA)
FACTS	Halla STATCOM (50MVA)

Table 2. Sensitivity analysis results

Bus number	Bus name	Sensitivity (normalized value)	Note
190	Halla	1.00	FACTS #2
210	Pyosun	0.99	
200	Seongsan	0.98	
140	Sin-Jeju	0.98	FACTS #1
310	Seo-Jeju	0.97	
180	Sinseogwi	0.96	
150	Hallim CC	0.95	
330	Hallim	0.95	
350	Jocheon	0.92	

5.2 CASE II-1 : FACTS control using the EQR module

If the first condition is satisfied (GV margin > 1) in the proposed algorithm in Fig. 7, the next condition (EQR margin) should be checked for stable system operation. If both conditions (GV margin > 1 and EQR margin > criterion) are satisfied in the proposed algorithm, the power system will be stable in the event of the designated contingency. However, even if the GV margin condition is satisfied, FACTS coordinated control is necessary if the EQR margin is small. In case II-1 and II-2, a change in the FACTS operating point was simulated considering a shortage of EQR margin. The EQR criterion is set up by the system operator and was assumed to be 90 MVar in this study. The power system conditions were identical to those of case I, and the applied contingency was a two-circuit fault between bus 130 and 140.

Table 4 shows two result of the EQR margin calculation. One is EQR margin under initial conditions and the other is

Table 3. New operating points based on the results of the sensitivity Analysis

Condition	FACTS state	
	Sin-Jeju STATCOM	Halla STATCOM
Initial operating point	4.5 MVar (Inductive)	5.4 MVar (Inductive)
After GV analysis	13.2 MVar (Inductive)	14.6 MVar (Inductive)

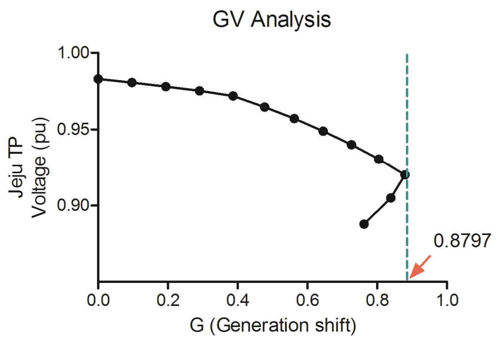

Fig. 8. GV analysis result (initial operating point)

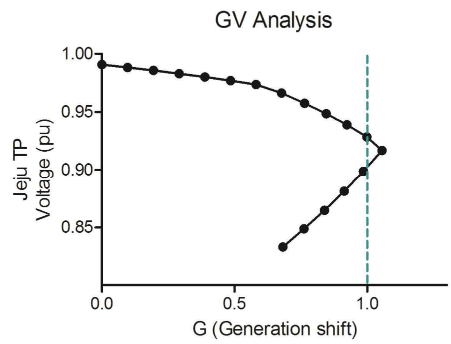

Fig. 9. GV analysis result (new operating point)

Table 4. EQR margin calculation result – before and after FACTS control. (Case II-1)

Bus number	Bus name	EQR margin (before)	EQR margin (after)
120	Jeju TP	162.785	192.078
121	Jeju CS	162.807	193.504
122	Jeju TS	162.788	192.516
130	Dong-Jeju	138.548	156.136
150	Hallim CC	107.176	121.868
160	Anduk	198.842	205.571
170	Nam-Jeju	209.473	214.937
180	Sinseogwi	123.304	132.606
200	Seongsan	154.478	168.101
210	Pyosun	144.222	157.892
220	Sanji	138.548	151.726
310	Seo-Jeju	63.391	93.150
330	Hallim	107.247	116.843
350	Jocheon	181.553	193.003
360	Gumak	124.144	130.056

Table 5. New operating point considering EQR. (Case II-1)

Condition	FACTS state	
	Sin-Jeju STATCOM	Halla STATCOM
Initial operating point	19.458 MVar (Capacitive)	50 MVar (Inductive)
After guaranteeing EQR margin	13.017 MVar (Inductive)	49.995 MVar (Inductive)

Table 6. EQR margin calculation result – before and after FACTS control. (Case II-2)

Bus number	Bus name	EQR margin (before)	EQR margin (after)
120	Jeju TP	149.981	165.092
121	Jeju CS	149.967	165.069
122	Jeju TS	149.971	165.073
130	Dong-Jeju	148.433	168.098
150	Hallim CC	132.633	152.054
160	Anduk	197.114	208.692
170	Nam-Jeju	200.965	212.837
180	Sinseogwi	118.557	125.629
200	Seongsan	115.201	131.495
210	Pyosun	101.109	126.303
220	Sanji	148.433	168.098
310	Seo-Jeju	77.355	95.851
330	Hallim	132.700	152.114
350	Jocheon	142.313	159.280
360	Gumak	139.042	156.284

Table 7. New operating point considering EQR. (Case II-2)

Condition	FACTS state	
	Sin-Jeju STATCOM	Halla STATCOM
Initial operating point	8.073 MVar (Inductive)	28.876 MVar (Inductive)
After guaranteeing EQR margin	20.484 MVar (Inductive)	40.985 MVar (Inductive)

after FACTS control. In the first result, the EQR margin of bus 310 was 63.391 and did not meet the criterion. The FACTS operating point therefore needed to be changed using the proposed control algorithm to secure the EQR margin. A new operating point was calculated by simulation and the result is shown in Table 5. The second result in Table 4 shows the EQR margin result after FACTS control. The EQR margins of all buses meet the criterion (over 90 MVar). Therefore, the power system has a sufficient EQR that would be determined by the system operator after FACTS control, and system stability can be guaranteed.

5.3 CASE II-2 : FACTS control using the EQR module

Table 6 shows additional simulation results of EQR module (using another data). The applied contingency is also identical to those of case I but the configuration of power system is different from CASE II-1's one. So the values of EQR are also varied compared to the result of CASE II-1.

The EQR margin of bus 310 was a problem so the FACTS operating point should be changed to secure the margin. A new operating point was calculated by simulation and the result is shown in Table 7. The second result in Table 6 shows the EQR margin result after FACTS control. The EQR margins of all buses meet the criterion (over 90 MVar).

6. Conclusion

This paper presents a multiple FACTS control algorithm in an island power system. Two modules in the proposed algorithm are used to set up an efficient operating point. First, a power flow calculation for an island power system is possible under abnormal conditions using a GV module based on GV analysis. The voltage collapse point of the system can be analyzed using the GV module, and a stable operating point for a FACTS can be calculated. Second, an effective reactive power reserve is calculated in the EQR module, instead of the conventional reactive power. Hence the reactive spinning reserve of a FACTS can be calculated. Finally, based on these two modules, the proposed algorithm describes a method for setting up the optimal operating point of a FACTS for voltage control. The Jeju Island power system is selected for simulation case studies and the results of simulations of this system show the validity of the algorithm.

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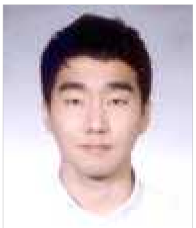

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