Coordination Control of Voltage Between STATCOM and Reactive Power Compensation Devices in Steady-State

Ji-Ho Park* and Young-Sik Baek[†]

Abstract – This paper proposes a new coordinated voltage control scheme between STATCOM (Static Synchronous Compensator) and reactive power compensation devices, such as shunt elements(shunt capacitor and shunt reactor) and ULTC(Under-Load Tap Changer) transformer in a local substation. If STATCOM and reactive power compensators are cooperatively used with well designed control algorithm, the target of the voltage control can be achieved in a suddenly changed power system. Also, keeping reactive power reserve in a STATCOM during steady-state operation is always needed to provide reactive power requirements during emergencies. This paper describes the coordinative voltage control method to keep or control the voltage of power system in an allowable range of steady-state and securing method of momentary reactive power reserve using PSS/E with Python. In the proposed method of this paper, the voltage reference of STATCOM is adjusted to keep the voltage of the most sensitive bus to the change of loads and other reactive power compensators also are settled to supply the reactive power shortage in out range of STATCOM to cope with the change of loads. As the result of simulation, it is possible to keep the load bus voltage in limited range and secure the momentary reactive power reserve in spite of broad load range condition.

Keywords: STATCOM, Shunt elements, Coordinated voltage control, Reactive power reserve

1. Introduction

In order to meet continuously growing electricity demand, it is necessary to invest in power plants and transmission facilities. However, these investments can not get sustainable growth because of several environmental and economic constraints [1]. As a result, the control of reactive power in power system operations and planning are very important because of the lack of investments in transmission facilities and the inductive nature of the network. Reactive power is closely related to a voltage control and the current development of high-precision industries is meant to highlight the importance of voltage quality. From the load's perspective, the focus of reactive power is on the margins to collapse. Although, a generator can supply the shortage of reactive power, the transmission of reactive power over long distances causes a serious problem [2]. So, it ought to be compensated where it is needed. Therefore, the control for reactive power is essential in order to stabilize system voltage.

With the progress of power electronics, FACTS(flexible ac transmission system) devices make it possible to maximize the transmission efficiency and can be widely applied for the voltage control [3, 4]. In Korea, beginning with the installation of UPFC(unified power flow controller) at the 154kV Kangjin substation, the installation of FACTS devices has been expanding into other areas. STATCOM (Static Synchronous Compensator) can perform voltage regulation function in a robust manner because it generates or absorbs reactive power at a fast rate. The control of reactive power with FACTS devices can greatly contribute to stabilizing the voltage. The FACTS devices are very effective to maintain the voltage stability during systematic accident and the proper voltage level for both heavy and light load. But because these FACTS devices are typically high precision equipments, so it should be used in the most efficient way. Therefore it requires the cooperation of the conventional reactive power control equipments such as shunt capacitor, shunt reactor and OLTC(on-line tap changing) transformer.

There have been some approaches proposed to control voltage in a desired range by coordinating the reactive power compensators. In [6], authors proposed a method to improve the overall voltage profile by coordinating STATCON (Static Condenser) with capacitor banks and ULTC. But the criterion of choosing the control gain is very complicated and the securing reactive power reserve has not been taken into consideration. In [7], the coordination controller is proposed by using ANN (Artificial Neural Network) as a classifier for tap position, but it needs a lot of data for training the ANN and is applied to a specific case. In [8, 9], the coordinated control system between the SVC and ULTC of the distribution substation is proposed. The objective of the coordinated control of [8, 9] is to minimize the number of unnecessary tap operations and to provide a better voltage profile.

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Although SVC can compensate reactive power to maintain voltage in a desired voltage range, the STATCOM can more effectively control voltage because of its ability to compensate more reactive power rapidly during emergency state such as a system fault. If STATCOM is cooperatively used with conventional reactive power compensators including ULTC through well designed coordinated control algorithm, the target of the voltage control can be achieved during both steady-state and emergency-state. Unlike the reference papers [6-9], this paper proposes an effective method satisfying both voltage control of steady state and securing of momentary reactive power reserve. Especially, the voltage reference of STATCOM is adjusted to keep the voltage of the most sensitive bus to the change of loads.

In this paper, the coordination control algorithm is implemented by Python programming with an analysis engine of PSS/E [5].

2. Modeling of Reactive Power Control Devices

Among FACTS devices which control voltage magnitude of a bus, a STATCOM is modeled in this section. Also, switched-shunt and ULTC transformer which control voltage magnitude by tap changing are modeled. In this paper, the coordination algorithm for voltage magnitude control is implemented by coordination using these devices.

2.1 STATCOM

A STATCOM consists of one VSC(Voltage Source Converter) and shunt-connected transformer. Its equivalent circuit is shown Fig. 1(a). The STATCOM injects an almost sinusoidal current at the bus of connection. The injected current of variable magnitude can emulate an inductive or a capacitive reactance at the bus of connection with the transmission line because it is almost in quadrature with the line voltage. Fig. 1(b) shows the steady state FATCS model in PSS/E [5]. FACTS device types can be represented by properly selecting the data shown in Fig. 1 (b). The STATCOM model can be implemented by bypassing the series link in Fig. 1(b).
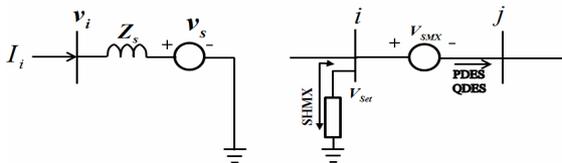
(a) Equivalent circuit　　(b) FACTS model in PSS/E

Fig. 1. STATCOM model

The power flow equations for the FATCS devices including STATCOM are derived from the equivalent circuits [10-12] and implemented in PSS/E.

2.2 Switched shunt

Fig. 2 shows the switched shunt model of PSS/E. The switching of circuit breakers(CB1, CB2) is operated by voltage relay. When the voltage magnitude at the switched-shunt bus is low, capacitor banks are added to the bus. When the voltage magnitude at the switched-shunt bus is high, reactor banks are added to the bus. Therefore, the switched-shunt elements at a bus may consist entirely of shunt capacitor banks or entirely of shunt reactor banks according to the operation of CB1 and CB2. At the bus i of Fig. 2, the linearised equation of reactive power of bus i can be expressed by the equation $\Delta Q_i = Q_i (\Delta B / B)$ and the susceptance B can be determined by using the relation of $B^i = B^{(i-1)} (\Delta B / B)^{(i)} B^{(i)}$ in the loadflow calculation .
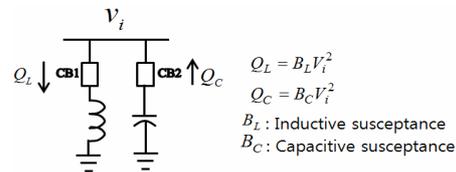

Fig. 2. PSS/E model of Switched-Shunt

2.3 ULTC transformer

ULTC transformer is fitted with a tap-changing mechanism to regulate the voltage magnitude from one of the transformer terminals. Fig. 3 shows the equivalent circuit of tap-changing transformer of PSS/E.
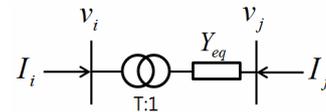

Fig. 3. The Equivalent Circuit of Tap Changing Transformer

In Fig. 3, the injection current and reactive power of bus i and j are as follows.

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \begin{bmatrix} Y_{eq}/T^2 & -Y_{eq}/T \\ -Y_{eq}/T & Y_{eq} \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix} \tag{1}$$

$$Q_i = -V_i B_{ii}/T^2 + V_i V_j \left[G_{ii} \sin(\theta_i - \theta_j) - B_{ii} \cos(\theta_i - \theta_j) \right]/T \tag{2}$$

$$Q_j = -V_j B_{jj}/T^2 + V_j V_i \left[G_{ji} \sin(\theta_j - \theta_i) - B_{ji} \cos(\theta_j - \theta_i) \right]/T \tag{3}$$

where $Y_{eq} = Y_{ii} = Y_{jj} = G_{ii} + jB_{ii} = G_{jj} + jB_{jj} = G + jB$
$Y_{ij} = Y_{ji} = -Y_{eq} = -G_{ij} - jB_{ij} = -G_{ji} - jB_{ji} = -G - jB$

In Eq. (2) and (3), the injection reactive power at bus is a function of tap variable T. Therefore, reactive power can be controlled by tap-changing. In the conventional loadflow

equation $\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}^{(i)} = -[J]\begin{bmatrix} \Delta\theta \\ \Delta V/V \end{bmatrix}^{(i)}$, if the voltage magnitude of the controlled bus is maintained constant at the target value and tap T is handled as a state variable, the loadflow equation is modified as equation $\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}^{(i)} = -[J]\begin{bmatrix} \Delta\theta \\ \Delta T/T \end{bmatrix}^{(i)}$ and the tap T to maintain the voltage magnitude at the controlled bus at a specified value can be obtained.

3. Proposed Algorithm

In steady state, because a STATCOM can response instantaneously to voltage fluctuation, the changed bus voltage is controlled by the STATCOM first, and when the STATCOM has reached its capacity limit, other reactive power compensators participate in controlling the bus voltage. However, in case of emergency state such as a system fault, as the STATCOM can response effectively to the voltage change of a bus, it is always required for the STATCOM securing a reasonable quantity of reactive power reserve. Moreover, there is a need to minimize the number of switching of the mechanical shunt device such as switched-shunt because of maintenance cost. According to these requirements, it is necessary to find out coordination control method between STATCOM and conventional reactive power controllers. In this paper, the proposed algorithm is implemented by using Python script and the result is used to apply for PSS/E. The PSS/E makes it possible for user to access the system by using a Python script.

3.1 Coordinative voltage control algorithm

A substation equipped with shunt FACTS device (STATCOM) and reactive power compensators is shown in Fig. 4. The voltage fluctuation at a bus is caused by the load variation of power system. In steady state, a decrease in load at a bus leads to an increase in bus voltage, an increase in load at a bus leads to a decrease in bus voltage. On a day basis, the bus load decreases in the early morning and the bus load increases in the daytime. If voltage
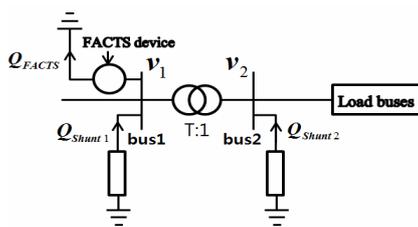
Fig. 4. A substation equipped with shunt FACTS device and reactive power compensators

magnitude fluctuates with load variation at a bus, the changed voltage at a bus is controlled by a STACTCOM first, a switched-shunt goes into operation second, and lastly, a ULTC goes into operation.

In Fig. 4, the voltages of load buses are more sensitive to the voltage change of bus2 than that of bus1. Therefore, the voltages of load buses can be more effectively controlled by regulating the voltage of bus2. In the proposed algorithm, the reference voltage of STATCOM is adjusted in response to the bus2's voltage change which is minimized through coordination control between the STATCOM and reactive power compensators. The sensitivity of voltage V_2 to reactive power compensators can be derived from the fast decoupled power flow algorithms [13]. From (2) and (3), the reactive power deviation can be represented by (4) with the simplified Jacobian matrix [13].

$$[J]\begin{bmatrix} \Delta V_i \\ \Delta V_j \end{bmatrix} = \begin{bmatrix} \Delta Q_i \\ \Delta Q_j \end{bmatrix} \tag{4}$$

Where $[J] = \begin{bmatrix} -\dfrac{B}{T^2} - \dfrac{B}{T} & -\dfrac{B}{T} \\ -\dfrac{B}{T} & -\dfrac{B}{T^2} - \dfrac{B}{T} \end{bmatrix}$

Multiplying by, $[J]^{-1}$

$$\begin{bmatrix} \Delta V_i \\ \Delta V_j \end{bmatrix} = [J]^{-1}\begin{bmatrix} \Delta Q_i \\ \Delta Q_j \end{bmatrix} = \begin{bmatrix} a & b \\ b & a \end{bmatrix}\begin{bmatrix} \Delta Q_i \\ \Delta Q_j \end{bmatrix} \tag{5}$$

Where $a = -\dfrac{1}{B}(\dfrac{1}{T^4} + \dfrac{2}{T^3})(\dfrac{1}{T^2} + \dfrac{1}{T})$

$b = -\dfrac{1}{B}(\dfrac{1}{T^4} + \dfrac{2}{T^3})\dfrac{1}{T}$

For a given voltage deviation, ΔV, the reactive power deviation, ΔQ, can be calculated by (4). However, we are interested in control of ΔV by reactive power compensators. Using (5), the voltage deviation in bus2 of Fig. 4 is as follow.

$$\Delta V_2 = |V_2 - V_2^{\text{target}}| = b\Delta Q_1 + a\Delta Q_2 \tag{6}$$

Where $\Delta Q_1 = \Delta Q_{FACTS} + \Delta Q_{shunt1}$
$\Delta Q_2 = \Delta Q_{shunt2}$

The values of ΔQ_{FACTS}, ΔQ_{shunt1} and ΔQ_{shunt2} to control ΔV_2 can be calculated by the proposed algorithm. The proposed algorithm is shown in Fig. 5. There are five control modes in Fig. 5.

Mode1: STATCOM is in its capacity limit. It is a situation that the target voltage(V_2^{target})of bus2 is controlled by only STATCOM. If the current voltage setpoint of STATCOM is V_{set}, the new value of V_{set} is calculated as follow:

$$V_{set}^{new} = V_{set} - S \times \Delta V_2^{\text{target}} \tag{7}$$

where $S = \Delta V_{set} / \Delta V_2$ is voltage sensitivity.

Mode2: The STATCOM doesn't meet capacity limit and $V_2 > V_2^{\text{target}}$. In this case, the reactive power supply of switched-shunt is decreased.

if $Q_{shunt2} \mathrel{!=} Q_{shunt2}^{\text{lowerlimit}}$,then $Q_{shunt2}^{i} = Q_{shunt2}^{i-1} - Q_{shunt2}^{step}$
else if $Q_{shunt1} \mathrel{!=} Q_{shunt1}^{\text{lowerlimit}}$, then $Q_{shunt1}^{i} = Q_{shunt1}^{i-1} - Q_{shunt1}^{step}$

Mode3: The STATCOM doesn't meet capacity limit and $V_2 < V_2^{\text{target}}$. In this case, the reactive power supply of switched-shunt is increased.

if $Q_{shunt2} \mathrel{!=} Q_{shunt2}^{\text{upperlimit}}$,then $Q_{shunt2}^{i} = Q_{shunt2}^{i-1} + Q_{shunt2}^{step}$
else if $Q_{shunt1} \mathrel{!=} Q_{shunt1}^{\text{upperlimit}}$, then $Q_{shunt1}^{i} = Q_{shunt1}^{i-1} + Q_{shunt1}^{step}$

Mode4: The tap ratio of ULTC transformer is increased.
$Tap^{i} = Tap^{i-1} + Tap^{step}$

Mode5: The tap ratio of ULTC transformer is decreased.
$Tap^{i} = Tap^{i-1} - Tap^{step}$

The algorithm of Fig. 5 can be implemented by Python programming through use of PSS/E as an analysis engine. All execution commands in Fig. 5 are performed by Python using PSS/E. The algorithm of Fig. 5 can be implemented by Python programming through use of PSS/E as an analysis engine. All execution commands in Fig. 5 are performed by Python using PSS/E. In Fig. 5, Q_{FACTS} is the reactive power absorbed by STATCOM from bus1, Q_{shunt1} is the reactive power supplied by switched-shunt to bus1 within the limits ($Q_{shunt1}^{\text{lowerlimit}}$ and $Q_{shunt1}^{\text{upperlimit}}$) of its

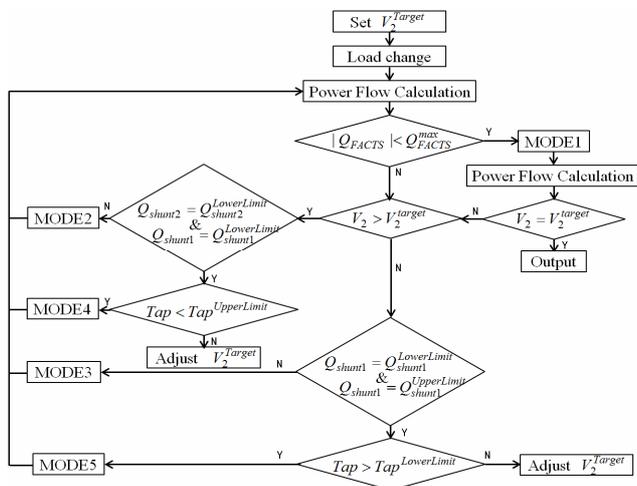capacity and the switched-shunt of bus2 supplies the reactive power of Q_{shunt2} within the limits($Q_{shunt2}^{\text{lowerlimit}}$ and $Q_{shunt2}^{\text{upperlimit}}$) of its capacity.

The quantity of reactive power controlled by switched-shunt in one step is Q_{shunt1}^{step} at the bus1 and Q_{shunt2}^{step} at the bus2. The target voltage V_2^{target} of bus2 to control voltage magnitude is specified and power flow calculation is executed to reflect the load variation of system. The expression of $V_2 = V_2^{\text{target}}$ is implemented as an expression of $|V_2 - V_2^{\text{target}}| < \varepsilon$ in Python script, where ε is a prescribed small tolerance. If the capacities of reactive power compensators are enough, the condition $|Q_{FACTS}| < Q_{FACTS}^{\max}$ is satisfied and the control of $|V_2 - V_2^{\text{target}}| < \varepsilon$ is accomplished by the control of Mode1.

3.2 Reactive power reserve algorithm

Securing reactive power reserve is required for voltage stability. Especially, in emergency state such as a fault, it is necessary to compensate reactive power quickly. These requirements can be satisfied by the FACTS device. Thus, a new algorithm is needed to secure momentary reactive power reserve while maintaining the target voltage. This paper represents the securing method of reactive power reserve under the assumption that the reactive power reserve quantity is given to ensure the voltage stability margin from the load's perspective.

From (6), $\Delta Q_{FACTS}^{\text{Reserve}} = Q_{FACTS}^{\text{ReserveTarget}} - Q_{FACTS}^{\text{Current}}$ is derived as follow:

$$\Delta Q_{FACTS}^{\text{Reserve}} = (\Delta V_2 - a\Delta Q_{shunt2} - b\Delta Q_{shunt1})/b \tag{8}$$

The values of ΔQ_{shunt1} and ΔQ_{shunt2} satisfying $\Delta Q_{FACTS}^{\text{Reserve}} < 0$ can be calculated by the proposed algorithm.

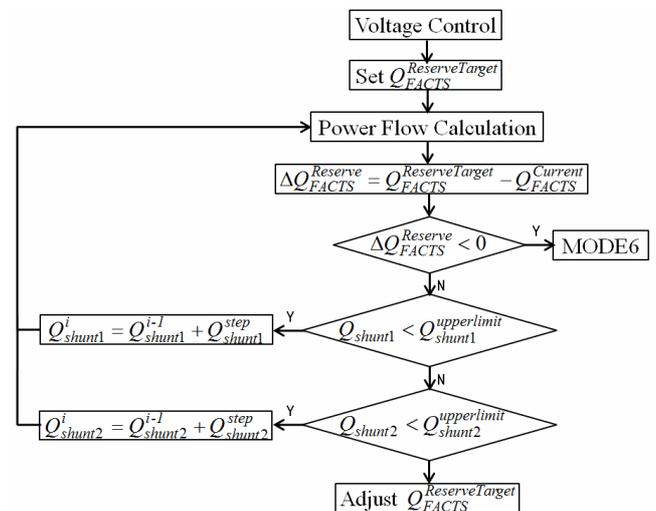An algorithm to secure momentary reactive power reserve is shown in Fig. 6.

Fig. 5. Coordinative voltage control algorithm

Fig. 6. Algorithm to secure reactive power reserve

Firstly, the voltage magnitude control is performed by using the algorithm of the Fig. 5. As the result of voltage magnitude control, if the current reactive power $Q_{FACTS}^{Current}$ of STATCOM is less than the reserve target $Q_{FACTS}^{ReserveTarget}$ to maintain, the switched-shunt of bus1 is injected first within its capacity limit. When the switched-shunt of bus1 has reached its capacity limit, the switched-shunt of bus2 is injected. If $Q_{FACTS}^{Current} > Q_{FACTS}^{ReserveTarget}$ is true, the control mode is Mode6.

In Mode6, the voltage deviation of bus2 is minimized within the margin of reactive power reserve. After the securing of reactive power reserve has finished, the voltage V_2 of bus2 is deviated from V_2^{target}. In Fig. 7(a), the margin of reactive power reserve($\Delta Q = Q_{FACTS}^{Current\,Re serve} - Q_t$) can be used to increase the voltage V_2 of bus2 by the equation $\Delta V_{set} = \Delta Q / S_{FACTS}$, where $S_{FACTS} = \Delta Q_{FACTS} / \Delta V_1$ is the reactive power sensitivity of STATCOM for the voltage change of V_1 and ΔV_{set} is incremental value of the reference voltage of STATCOM. The quantity of $Q_{FACTS}^{V_2 target}$ is obtained in the voltage control step of Fig. 5. In Fig. 7(b), $\Delta Q = Q_t - Q_{FACTS}^{Current\,Re serve}$ can be absorbed by STATCOM to decrease the voltage V_2 of bus2 by the equation $\Delta V_{set} = \Delta Q / S_{FACTS}$. In the situations of $Q_{FACTS}^{V_2 target} > Q_{FACTS}^{max}$ and $Q_{FACTS}^{ReserveTarget} > Q_{FACTS}^{V_2 target}$, the control of $V_2 = V_2^{target}$ is impossible. By using the process of Mode6, the voltage deviation of V_2 can be minimized within the margin of reactive power reserve.
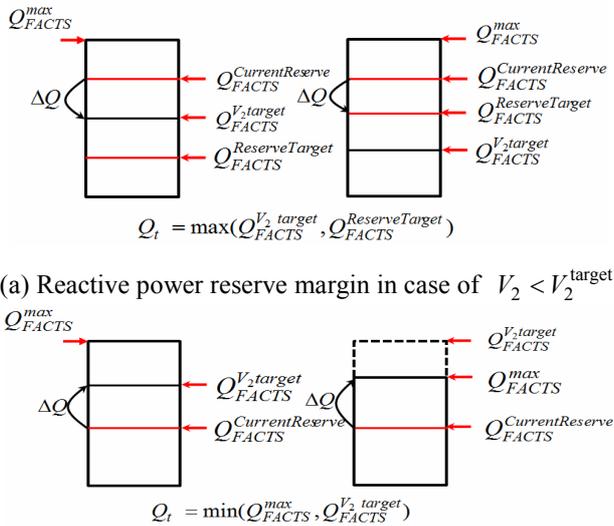
(a) Reactive power reserve margin in case of $V_2 < V_2^{target}$

(b) Reactive power reserve margin in case of $V_2 > V_2^{target}$

Fig. 7. Reactive power reserve margin in Mode6 after securing reactive power reserve

4. Case Study

4.1 Study system

Fig. 8 shows the diagram of the system studied in this paper. The study system includes the 345kV transmission lines, the reactive power compensators and the buses considering load change of the power system near Migum substation of KEPCO (Korea Electric Power Corporation) system. The loads of the rest buses not shown in Fig. 8 are assumed to be constant. In the case study, the equipments used for coordinative voltage control are a STATCOM ($\pm$100MVA), five shunt reactors(100MVAR$\times$5), six capacitors (50MVAR$\times$6) and ULTC transformers of the Migum substation.
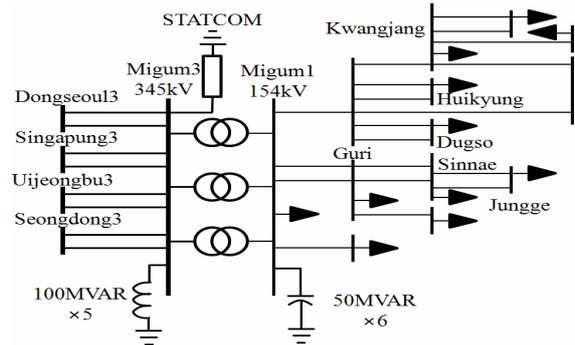

Fig. 8. Migum substation of KEPCO system

4.2 Voltage reference bus of STATCOM

The STATCOM is installed at the Migum3 bus, but it is effective to control the voltage of the Migum1 bus by using STATCOM to regulate the voltages of the neighboring load buses as well as the Migum1 bus. Two simulations are conducted to show the effectiveness of the voltage control of Migum1 bus by STATCOM. From the assumed initial total load of buses connected to Migum1, the step-by-step load increasing and decreasing are simulated with applying the arbitrary load change rate to initial loads. The first simulation case(SIM1) is that the voltage reference of STATCOM is the Migum3 345kV bus. The result of this case is shown in Fig. 9. The second simulation case (SIM2) is that the STATCOM's voltage reference is the Migum1 154kV bus and the result is shown in Fig. 10. When compared to the result of Fig. 9, the voltage deviations of load buses in Fig. 10 are very small because the load buses are connected to the Migum1 bus. The simulation results
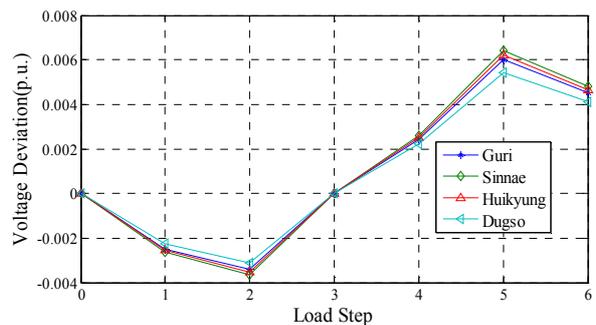

Fig. 9. The result of SIM1

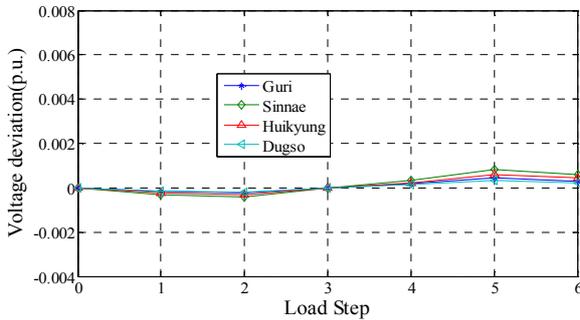show that the voltages of load buses are more effectively controlled by the second method.

Fig. 10. The result of SIM2

4.3 Coordinative voltage control results

The voltage sensitivity $S = 1.095$ is used in Mode1. This value is obtained by the simulation of the system. If the STATCOM is in its capacity limit, the voltage of Migum1 bus is controlled by Eq. (7) with the voltage sensitivity of $S = 1.095$. The hourly change rate of daily load curve is applied to the loads of the study system of Fig. 8. Fig. 11

shows the results of coordination control in case of $V_{Migum1}^{target} = 1.025\,p.u.$. At the load step0(initial loads), the proposed control algorithm is not applied. In the section of load decrease, the STATCOM is operating in inductive mode and the injection of three reactors is occurred. In the section of load increase, the STATCOM is operating in capacitive mode and three capacitors are injected. In Fig. 11(b), the voltage of Migum1 bus from load step1 to load step24 is almost constantly controlled as $V_{Migum1}^{target} = 1.025\,p.u.$ with the tolerance of $\varepsilon = 10^{-4}$.

As a result, the voltage fluctuations are very small in all load buses except for the Kwangjang bus. The voltage deviation of the Kwangjang bus is relatively large than other buses. The reason is as follows. The Kwangjang bus has largest complex loads in study system and the load change rate is applied to this bus at the same rate as the other buses. Therefore, the load change range of the Kwangjang bus is greater than the other buses. Fig. 12 shows the results of coordination control in case of $V_{Migum1}^{target} = 1.03\,p.u.$. Because the target voltage of Migum1 bus is increased than that of previous simulation case, the total reactive power absorption of shunt reactors is decreased and the total reactive power supply of shunt capacitors is increased. However, the voltage fluctuation of load buses shows the pattern similar to that of previous simulation case.
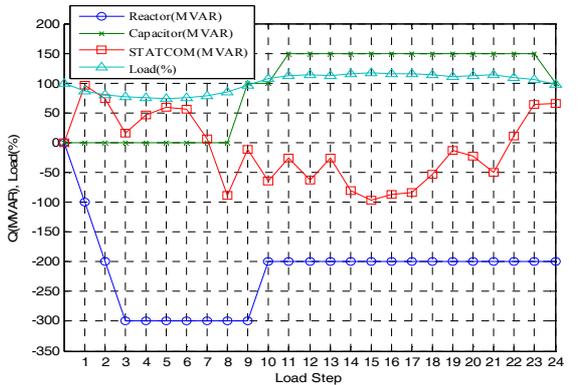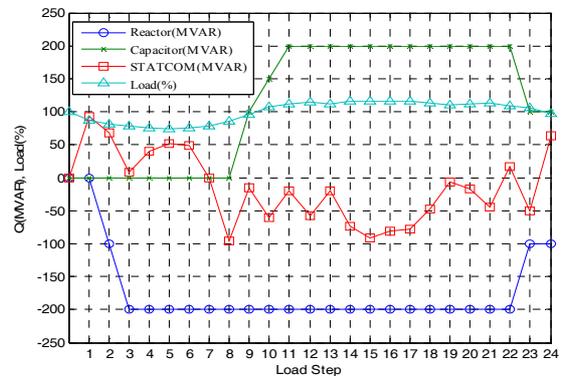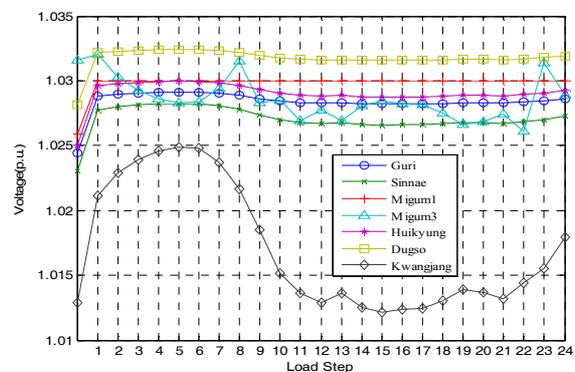

(a)
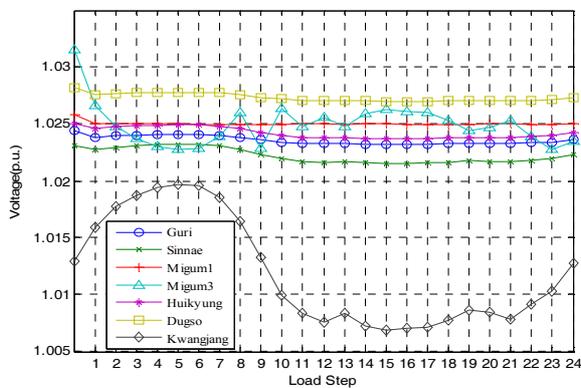
(b)

Fig. 11. Simulation results in case of $V_{Migum1}^{target} = 1.025\,p.u.$


(a)

(b)

Fig. 12. Simulation results in case of $V_{Migum1}^{target} = 1.03\,p.u.$

4.4 Reactive power reserve results

Fig. 13 shows the results of a simulation case that secures the capacitive momentary reactive power reserve of more than 155MVAR while maintaining the reactive power absorption of more than 55MVAR by the STATCOM. In Fig. 13(a), the number of injected shunt reactors is less than that of Fig. 11(a) because of STATCOM's reactive power absorption to secure momentary reactive power. In Fig. 13(b), the voltage fluctuations of load buses are greater than those of Fig. 11(b). However, because the voltage of Migum1 bus is controlled by the method of MODE6 with the target voltage of $V_{Migum1}^{target} = 1.025 p.u.$ in the process of securing the reactive power reserve, the voltage fluctuations of Fig. 13(b) are minimized within the limit of reactive power reserve margin explained in Fig. 7. The voltage V_{Migum1} of Migum1 bus is controlled at average of 1.0257p.u. The maximum positive deviation of the V_{Migum1} on the target voltage $V_{Migum1}^{target} = 1.025 p.u.$ is 0.001943p.u and maximum negative deviation is -0.00199p.u..
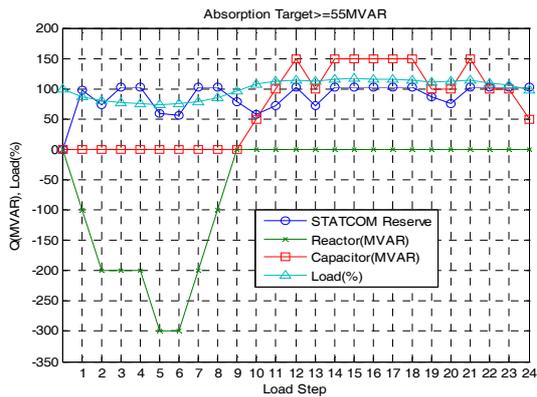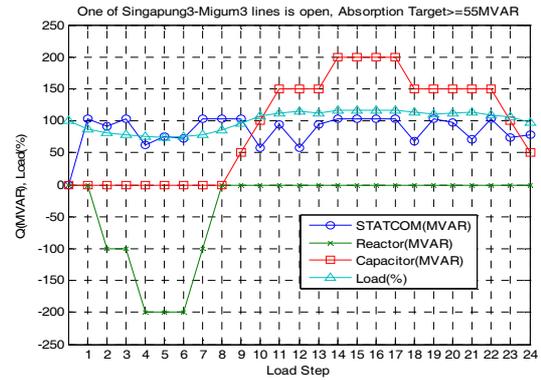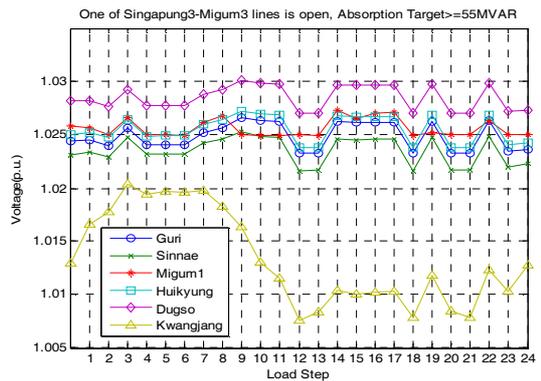

(a)
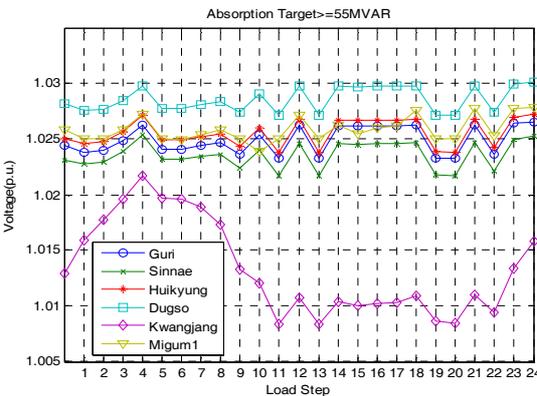
(b)

Fig. 13. Simulation results in case of STATCOM's absorption target of more than 55MVAR

Fig. 14 shows the results of a simulation case that the reactive power of more than 55MVAR is absorbed by

STATCOM under the state that one of Singapung3-Migum3 lines is open. The reactive power supplied through 345kV transmission lines is decreased because one of Singapung3-Migum3 lines is open. When compared to Fig. 13(a), while the reactive power absorption of reactors is decreased, the reactive power supply of capacitors is increased. And, the total number of switching of shunt devices(reactors and capacitors) is decreased.
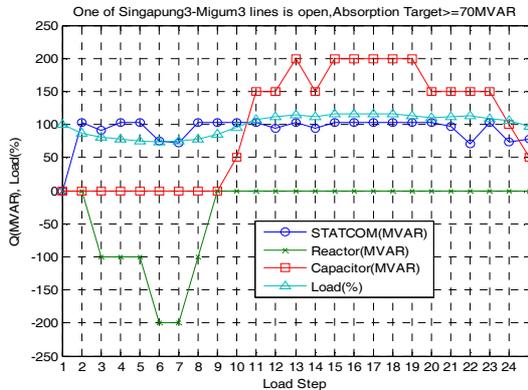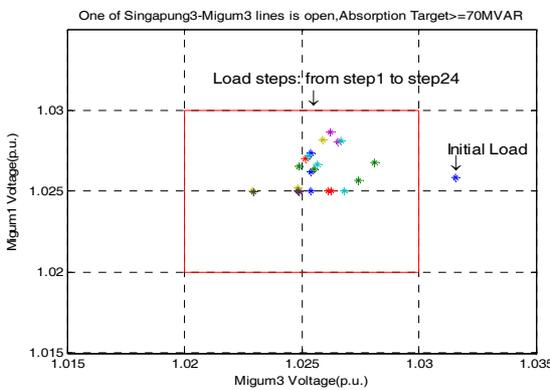

(a)

(b)

Fig. 14. Simulation results in case one of Singapung3-Migum3 lines is open(absorption target>=55MVAR)

Fig. 15 shows the results of a simulation case that the reactive power of more than 70MVAR is absorbed by STATCOM under the state that one of Singapung3-Migum3 lines is open. In Fig. 15(a), the shunt devices show the switching patterns similar to those of Fig. 14(a). However, the total reactive power absorption of shunt reactors is decreased and the total reactive power supply of shunt capacitors is increased. Because the absorption target of STATCOM of Fig. 15(a) is greater than that of Fig. 14(a), the reactive power reserve margin is smaller than that of Fig. 14(a). Therefore the voltage deviation of Migum1 bus is increased. The voltage control target of Migum1 bus is $V_{Migum1}^{target} = 1.025 p.u.$. Fig. 15(b) shows the voltage deviation of Migum1 bus when the loads change from load step1 to load step24. The maximum voltage deviation is 0.0037p.u.. At the point of initial load, all

345kV transmission lines are closed and the proposed control algorithm is not applied.

(a)

(b)

Fig. 15. Simulation results in case one of Singapung3-Migum3 lines is open(absorption target>=70MVAR)

Fig. 16 shows the results of a simulation case that the reactive power of more than 70MVAR is absorbed by STATCOM with $V_{Migum1}^{target} = 1.025\,p.u.$ under the state that one of 345kV transmission lines is open at the initial loads.
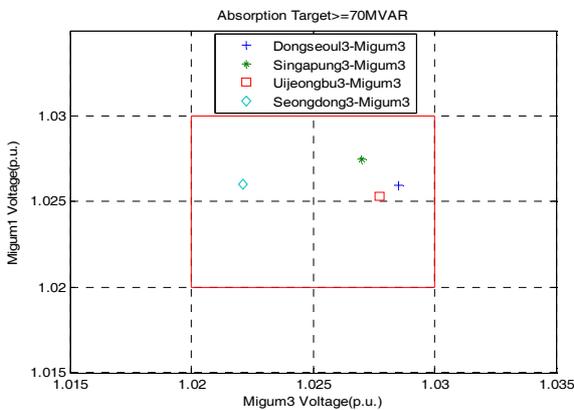

Fig. 16. Simulation results in case one of 345kV transmission lines is open(absorption target>=70MVAR)

In the simulation of Fig. 16, when one of Singapung3-Migum3 lines is open, the voltage of Migum1 bus has the largest deviation from target voltage. But it is possible to secure the target of reactive power reserve under all the situations that any a 345kV transmission line is open.

5. Conclusion

In this paper, when the change of bus voltage magnitude due to the change of bus load is occurred, the method of voltage magnitude control and securing reactive power reserve for emergency state is implemented by coordination control between STATCOM and conventional reactive power compensators. The proposed method is implemented through Python programming using PSS/E as an analysis engine. This paper presents the detailed coordination control method that is simulated to real power system. The simulation results show that the voltage deviation due to load change is effectively controlled by adjusting the voltage setpoint of STATCOM to the most sensitive bus to the change of load. In addition, by using the proposed coordination among the reactive power compensators in this paper, securing momentary reactive power reserve can be implemented. After the securing of reactive power reserve has finished, the voltage deviation of load bus can be minimized by adjusting STATCOM's reference voltage within the margin of reactive power reserve. The operation points of the conventional reactive power compensators and the voltage setpoint of STATCOM for any a substation system can be determined by the simulation using the proposed method. This method makes it possible to minimize the number of switching of the mechanical shunt devices of a real substation system.

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