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# Hybrid Secondary Voltage Control combined with Large-Scale Wind Farms and Synchronous Generators

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**Abstract** – For stable integration of large-scale wind farms, integration standards (Grid codes) have been proposed by the system operator. In particular, voltage control of large-scale wind farms is gradually becoming important because of the increasing size of individual wind farms. Among the various voltage control methods, Secondary Voltage Control (SVC) is a method that can control the reactive power reserve of a control area uniformly. This paper proposes hybrid SVC when a large-scale wind farm is integrated into the power grid. Using SVC, the burden of a wind turbine converter for generating reactive power can be reduced. To prove the effectiveness of the proposed strategy, a simulation study is carried out for the Jeju system. The proposed strategy can improve the voltage conditions and reactive power reserve with this hybrid SVC.

**Keywords**: Grid code, Large scale wind farms, Voltage/reactive power control, Secondary voltage control

## 1. Introduction

Recently, interest in renewable energy has been gradually increasing because of the depletion of fossil fuels and limits on greenhouse gas emissions. Among renewable energy sources, the most technologically advanced and economical source is wind energy. Thus, the penetration of wind power has rapidly increased worldwide. In the past, wind power had little effect on the stability of the power system because the penetration of wind power was small. However, the impact of wind power has gradually increased in importance because of the increasing penetration of wind power in power systems [1]. In particular, the variability of wind and the control instability of wind generators largely influence the stability of a power system. This variability of wind power can cause a wide-area blackout because of its adverse effect on the stability and security of the power system. Therefore, the operators of power systems are presented with the Grid Code for reliably linking large-scale wind power to the power grid. The contents of the Grid Code are presented such that large-scale wind farms should have variable controllability, as with existing generators. The fast development of wind power technology has resulted in substantial impacts on the operation and control of the grid, such as voltage control and frequency control. Among these Grid Codes, they have mainly focused on active power and frequency control of wind farms. Many studies have been conducted regarding this, and the operation of large-scale wind farms has been applied to these studies. However, the concern for the voltage and reactive power control of wind farms has been gradually increasing because of the increasing penetration of wind power in power systems.

In 2011, three serious accidents occurred for a mass of wind turbines in China that disconnected from the grid owing to improper control of the reactive power [2]. Therefore, various countries and companies have created rules regarding reactive power and voltage control [1, 3]. The Grid Codes related to the reactive power and voltage control of wind farms are specified in [3]. Several codes mainly express the reactive power requirements and voltage control at the point of interconnection (POI). In Denmark, Germany, and Spain, there is a provision for power factor control, reactive power control, or voltage control in their Grid Codes. The German transmission Grid Code only states that generator voltage control must take immediate action when the voltage changes. A new set point must be implemented within 1 min. In Denmark, set point changes must be implanted within 10 s, and there is a provision for a droop setting. Reactive power control is performed in order to control the set point by configuring the set point of the bus voltage. The reactive power output is adjusted by considering the droop setting in accordance with the individual wind power generator. In Spain, the slope can range between 0 and 25 (Mvar p.u./Voltage deviation p.u), and the entire response to a change must be achieved within 1 min. This method is established as provision OP 12.2 [4]. The voltage is controlled by adjusting the reactive power output by selecting the slope in accordance with the system characteristics of the voltage error in order to control the specific bus voltage. Various

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types of studies have been conducted in order to satisfy this Grid Code conditions of reactive power and voltage control as shown above. Traditionally, voltage and reactive power control has focused on the control of individual wind turbines to satisfy the Grid Code. In particular, in the case of a Type-3 or Type-4 wind turbine, the above condition is satisfied by converter control because the converter can control the reactive power. However, a wind farm comprises a number of individual wind turbines integrated at POI, whereas traditional generator control is for only one generator and only POI. Therefore, control for a wind farm should be centralized rather than having each generator individually controlled for voltage and reactive power control [4].

For previous wind power voltage and reactive power control, the purpose was to maintain the voltage at the POI between the wind farm and the system. However, the ability to maintain the voltage of the system, as in synchronous generators, is required, as the size of a wind farm has become larger. Synchronous generators use various methods for voltage control in order to maintain the voltage within a system. In Europe, the secondary voltage control (SVC) method is used in order to maintain the system voltage. The SVC method divides the control area in order to control the system voltage and performs generator terminal voltage control to maintain the voltage of the representative bus by selecting it within the area. This control method facilitates the maintenance of the voltage within the control area by representative bus voltage control.

This paper presents hybrid Secondary Voltage Control (HSVC) combined with large-scale wind farms and synchronous generators. This method is based on SVC. The chapter 2 examines the existing SVC system installed in the Jeju power system. The chapter 3 presents the expected wind resources integrated into the Jeju power system and discusses the doubly fed induction generator (DFIG) model used in this paper. The chapter 4 introduces the HSVC algorithm with large-scale wind power. The chapter 5 examines the application of HSVC to the Jeju power system to demonstrate the effectiveness of the proposed algorithm. The used tool for the simulation is the TSAT of the PowerTech [9].

## 2. Secondary Voltage Control (SVC) in the Jeju System

Currently, Jeju island in Korea uses SVC to regularly maintain the bus voltage in the Jeju area. This system is based on the hierarchical control system used in the European power grid for automatic voltage regulation. The hierarchical system is organized in the following level structure: Primary Voltage Control (PVC), Secondary Voltage Control (SVC) and Tertiary Voltage Control (TVC). The PVC controls the terminal voltage of the each generator by an Automatic Voltage Regulator (AVR) at the generation level. The time frame for PVC is a few seconds. SVC, which is based on the pilot point concept, controls the pilot bus voltage for generators in a given control area of the transmission network divided into control regions by electrical distance. The time frame for SVC is a few minutes.

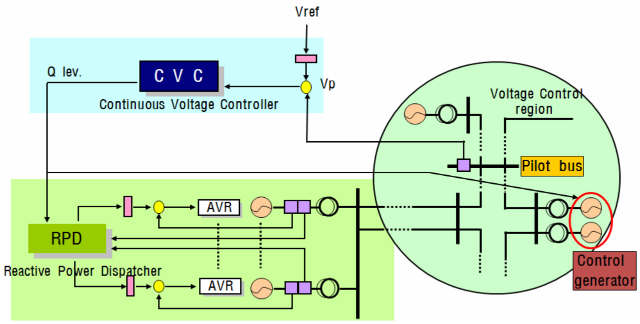


**Fig. 1.** Configuration of SVC

Fig. 1 shows the configuration of SVC. In order to apply SVC, the voltage control area is set at first. The voltage control area divides the part of the system that has the same voltage stability characteristics by the electrical distance. The bus that has the smallest sum of electrical distance with the other buses in the divided control area is selected and set as the pilot bus. As the pilot bus is maintained at the reference value, all buses in the voltage control area are controlled within the stable region. Next, the control generators that participate in SVC are determined by selecting the generator group that has the most sensitivity represented by the electrical distance with the pilot bus. In Fig. 1, SVC observes the voltage of the pilot bus and controls it when it deviates from the reference value. In Continuous voltage control (CVC), the amount of Q required to control the pilot bus within the range of the reference voltage is calculated by the PI control method. The calculated Q is distributed by the Reactive Power Dispatcher (RPD) of each control generator. In RPD of the control generators, $\Delta V$ is calculated to output the distributed amount of Q by I control. The calculated $\Delta V$ is controlled by using the generator AVR (Automatic Voltage Regulator), which controls the terminal voltage by an exciter [5]. When applying SVC, the maximum transport power increases by regulating the voltage of the

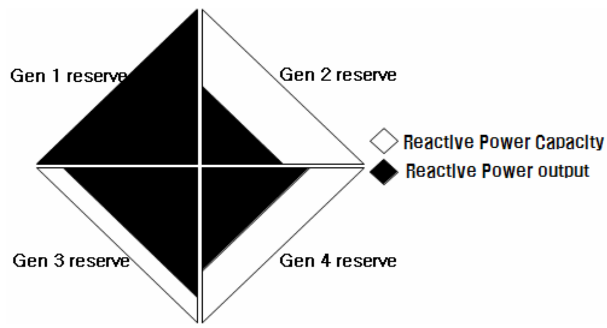


**Fig. 2.** Reactive power reserve of each generator

pilot bus that is closer to the load area than the generator bus. The balance of demand and supply for the reactive power of the system can be also maintained at a constant value by equalizing the reactive power between each control generator. Fig. 2 illustrates this concept.

Because the reactive power has local characteristics, all generators in the region do not have the same reactive power output. In Fig. 2, the situation in which a specific generator cannot control the reactive power because the limit of reactive power output has been met. In contrast, the other generators have sufficient reactive power reserves. SVC can maintain the balance of reactive power in the voltage control area because the control generator creates reactive power in proportion to their reactive power reserves in order to maintain the voltage of the pilot bus.

The Jeju system is applied to SVC [5]. The 2006 Jeju power system that first installed SVC had 460-MW loads during the summer peak. Because the size of the entire Jeju power system is not large, the control area is represented as one area by its electric distance. The pilot bus is selected in order to control the voltage of the Jeju area. From the sensitivity matrix, the JEJU TP bus was selected as the pilot bus. JEJU TP# 2, 3, NJEJU TP# 3, and HANLIM were selected as the control generators considering the sensitivity of the pilot bus and capacity. Control generators monitor the voltage of JEJU TP, and SVC control actions are performed when the voltage of the pilot bus is outside of the reference voltage range.

## 3. Wind Power in the Jeju system and DFIG Model

As the use of wind power increases worldwide, the wind power of the Jeju system is also increasing. Currently, JEJU power system of 600-MW loads are planned for the construction of 2-GW wind power facilities until 2030. Furthermore, the capacity of a single wind farm is similar to the existing generator in the Jeju system. Thus, the sensitivity for determining the control generator can include the large-scale wind farms. The wind generators have different ways of controlling the reactive power from the synchronous generators that control the reactive power and voltage by terminal voltage control using the exciter current. Type-1- and Type-2-based induction generators cannot control the reactive power and voltage by the generator itself. Wind generators that can control the reactive power and voltage are of Types 3 and 4; they can control the reactive power and voltage using converter control. In this paper, we use a Type-3 wind turbine (DFIG). The stator winding of a Type-3 wind turbine is directly connected to the grid while its rotor winding is connected to rotor-side convertor as the back-to-back IGBT voltage source converter in Fig. 3.

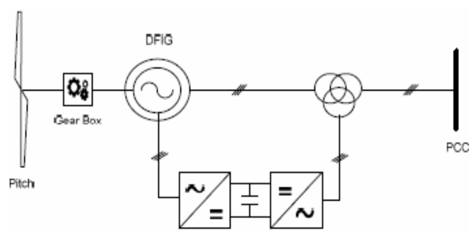


**Fig. 3.** Configuration of the DFIG

The converter can control in decoupling the mechanical and electrical frequency and variable-speed operation is possible. Because the Type-3 is equipped with a partial scale converter, it cannot operate within the full range from zero to the rated speed. However, the speed range is quite sufficient [1, 4].

A wind turbine has variable power output depending on the wind conditions. Typically, in the case of setting the power flow in a Type-3 wind turbine, the active power is typically determined first according to the wind conditions, and then, the reactive power min-max value is determined according to the desired power factor. Eq. (1) expresses these characteristics [6, 7]:

$$-Q_{\min} = Q_{\max} = P_g \tan(\cos^{-1}(PF)) \tag{1}$$

where :
$P_g$ : active power output of the wind turbine generator
PF : power factor which wants to operate

If the power factor of the wind generator is not fixed, the values are determined according to the power factor range and value. A value of 0.95 is applied as the PF for the wind turbine. In general, there are two ways of steady-state simulating the wind power generators at the transmission level generally. One method models each generator in a wind farm one by one at the generator level. This method is applied when the amount of connected wind power is small, and the simulation is performed at the distribution concept. When the amount of wind power at the transmission level is large, many wind power generators in wind farms are simulated by aggregating them as one.

Fig. 4 shows the aggregation model of large-scale wind farms [7]. The P output of generators is considered in aggregation modeling. When N numbers of single generators with a rating of $P_{rated}$ are connected, the output P is calculated by Eq. (2).

$$P_g = N \times P_{rated} \tag{2}$$

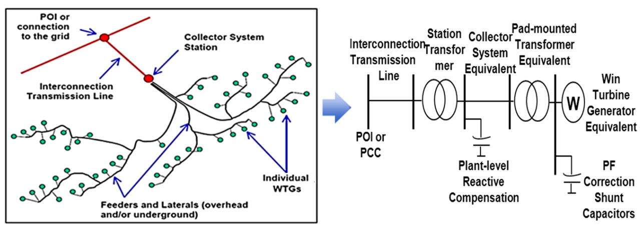


**Fig. 4.** Equivalent process of wind farms

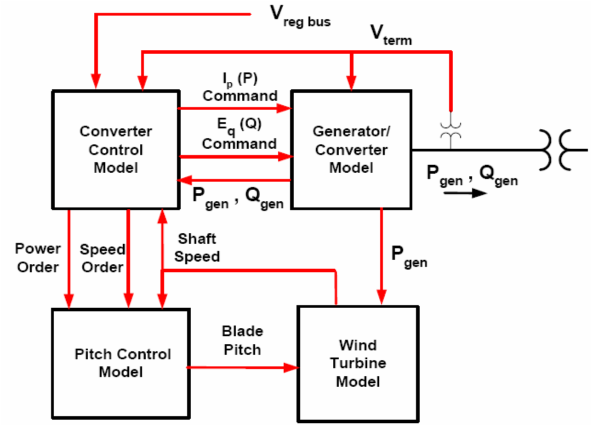


**Fig. 5.** Model block of the DFIG

When P is calculated, $Q_{\min}$ and $Q_{\max}$ are determined by Eq. (1). This paper uses the aggregation model as shown above, since it focuses on the SVC algorithm by cooperative operation with other synchronous generators when the large-scale wind farm connects to the power system.

This paper uses a DFIG as a wind power generator. In WECC, a generic model is suggested in order to interpret the system of wind power generators at the transmission level. Fig. 5 shows the diagram of the generic model of the DFIG.

The generic model of the DFIG can be divided into four main parts. These parts consist of the 'Generator/Converter Model' that controls the final power generator output, the 'Wind Turbine Model' that considers the mechanical characteristics according to the axis of the shaft, the 'Pitch Control Model' that controls the output by adjusting the blade pitch in accordance with the wind output, and the 'Converter Control Model' that regulates the voltage and the reactive power output through the converter. This paper adjusts the Converter Control Model in order to apply voltage and reactive power control for the wind power generator [8]. There are three operating modes in the converter of the WECC DFIG generic model. These modes include the 'Voltage Control Mode' that maintains the voltage, the 'Reactive Power Control Mode' that controls the converter Q output, and the 'Power Factor Control Mode' that maintains the PF depending on generator output P [9].

## 4. Hybrid Secondary Voltage Control System

This paper proposes a HSVC system combined with a large-scale wind generator and thermal generator by considering the difference in the reactive power characteristics of each generator. For the existing SVC, CVC calculates the control signals for the generation reactive power level (Q%) by using the PI control. Eq. 3. shows this methods.

$$\dot{e}_r(t) = V_{P\_REF}(t) - V_p(t)$$
$$Q_G\%(t) = K_{PC}\cdot \dot{e}_r(t) + \int K_{IC}\cdot \dot{e}_r(t)dt \qquad (3)$$

where,
$V_p(t)$ : Voltage of the pilot bus at time t
$V_{P,REF}(t)$ : Voltage reference at time t derived from TVC or the operator $Q_G\%(t)$ : Reactive power level to be generated in the RPD of each generator $K_{PC}, K_{IC}$ : Proportional and integral gains, respectively, in the PI controller

The calculated signals are sent to the RPD of each generator by a communication system where the Q level is compared with the present reactive power output, and the generator terminal voltage is adjusted using I control. Eq. (4). shows this I control method [5].

$$\dot{e}_q(t) = Q_{G\_REF}(t) - Q_G(t)$$
$$Q_{G\_REF}(t) = Q_G\%(t)\cdot Q_{G\_Min/Max}(t) \qquad (4)$$
$$\Delta V_G(t) = \int K_{IR}\cdot \dot{e}_q(t)dt$$

where :, $Q_G(t)$ : Reactive power output of each generator at time t $Q_{GREF}(t)$ : Reactive power reference of the RPD at time t calculated from Eq. (3) $Q_G\%(t)$ : Reactive power level to be calculated from CVC $Q_{GMin/Max}(t)$ : Upper and lower reactive power limits of each generator $K_{IR}$ : Integral gain of the RPD

In each generator, an AVR controls the generator terminal voltage. Therefore, the voltage of the pilot bus can be maintained at reference voltage.

Fig. 6 shows the schematic of the algorithm proposed in this paper. In this paper, there is CVC in the central control center, such as the existing SVC. As before, CVC observes the voltage of the pilot bus. When the voltage of the pilot bus deviates from the reference voltage, the Q level that is required for voltage control is equally calculated by the PI

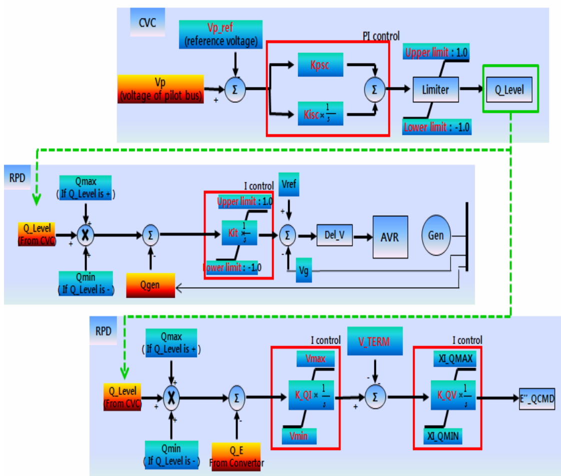


**Fig. 6.** Schematic of hybrid SVC

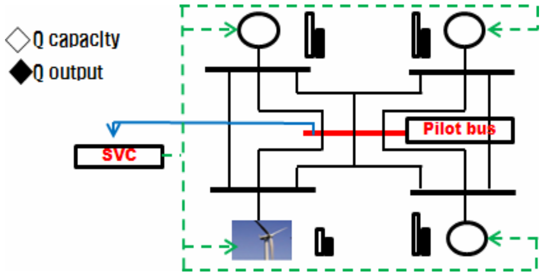


**Fig. 7.** Configuration of hybrid SVC

control, as in Eq.(3). At this time, the calculated Q level is distributed to each generator in proportion to each Q output of the generators. $\Delta V$ is computed by I control, as in Eq.(4), in order to produce the distributed Q level. In case of the existing synchronous generators, $\Delta V$ is calculated in the control generators to output the distributed amount of Q by I control. The calculated $\Delta V$ is controlled by using the generator AVR, which controls the terminal voltage by an exciter and Q is produced in order to maintain the pilot bus voltage. In case of the large-scale wind farms, the device of producing the reactive power is different from the existing synchronous generators. For the large-scale wind farms, convertor control is performed to produce the distributed Q level. As mentioned in chapter 3, there are three control modes for voltage and reactive power control in the DFIG converter. The algorithm in this paper applies 'constant Q mode' of the DFIG converter. When the distributed Q level at CVC is inserted as a Q reference for the 'constant Q mode' of the converter, the converter produces the appropriate Q through I control. Therefore, the pilot bus voltage is maintained at the reference value using coordinated operation combined with the synchronous generators and large-scale wind farm.

A situation in which the wind generator cannot control the reactive power or can disconnect from the grid can occur because of the limit of the reactive power reserve of the wind generator and the severe contingency of the grid. However, the HSVC in Fig. 7 can prevent this situation in which the wind farm limits the Q output because of the coordinated Q control between each generator. Furthermore, HSVC can also maintain the POI voltage by controlling the pilot bus.

## 5. Simulation Results for HSVC

This algorithm is applied to the Jeju system in Fig. 8. The pilot bus is a #120 bus (JEJU TP), and the reference voltage is 1.0275 p.u. This reference voltage is determined by [5].

The control generator is selected following Table 1 according to the sensitivity of the electrical distance [5].

HANLIM TP is changed to a wind generator with the same capacity by assuming that large-scale wind farms are integrated into the Jeju power system. Because the large-scale wind farms are included, the HSVC algorithm, which reflects the control characteristics of the wind power generators, is applied to maintain the pilot bus voltage. There are two aspects of the results. One is the aspect of the system, and the other is the aspect of the wind farm.

**Table 1.** Control generators in the HSVC

| | Active power generation | Sensitivity |
|---|---|---|
| JEJU TP#2 | 75 | 0.3595 |
| JEJU TP#3 | 75 | 0.3595 |
| HANLIM | 100 | 0.1203 |
| Njeju TP#3 | 100 | 0.1203 |

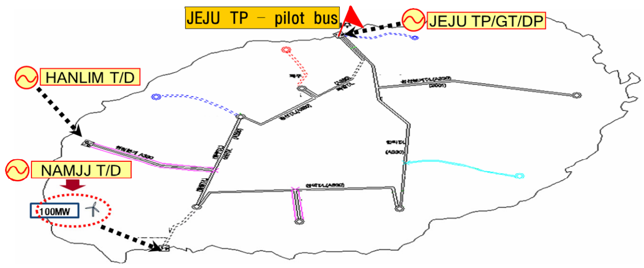


**Fig. 8.** Jeju system for the HSVC simulations

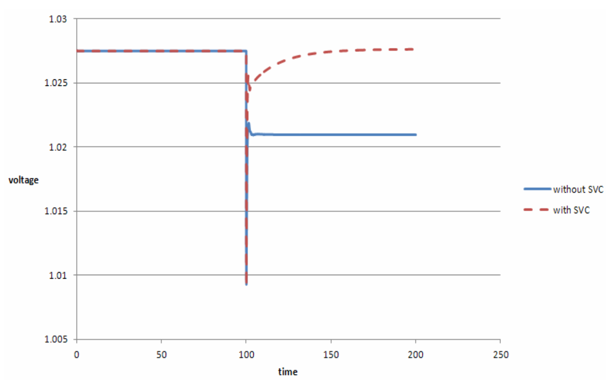


**Fig. 9.** Voltage of the 120 bus at first contingency

At first, following the results is the result from the aspect of system. The first contingency scenario is the increasing reactive load of 45 Mvar at 100s for monitoring the effectiveness of voltage control of the HSVC. Fig. 9 shows the simulation results for the first contingency. When the voltage of the pilot bus decreases according to the contingency, CVC is working. Then, the voltage of the pilot bus can be maintained at the reference voltage.

The second contingency scenario is the increasing reactive load of 90 Mvar at 100 s because of the assumed severe conditions. Fig. 10 shows the results of the simulation for the second contingency. When the voltage of the pilot bus decreases according to the severe increasing reactive power loads, CVC is working. Then, the voltage of the pilot bus can be maintained at the reference voltage. CVC can prevent a voltage collapse of the system caused by long-term voltage instability.

SVC is helpful for wind generators in terms of reactive

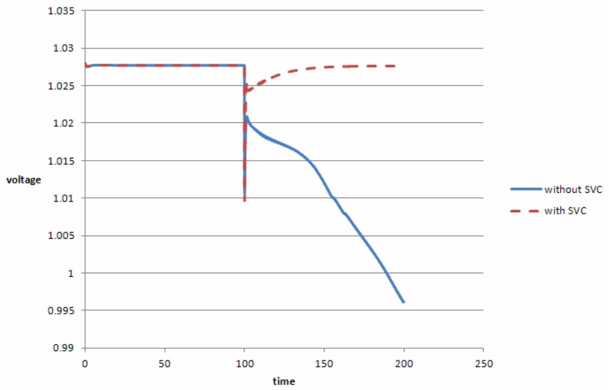


**Fig. 10.** Voltage of the 120 bus at second contingency

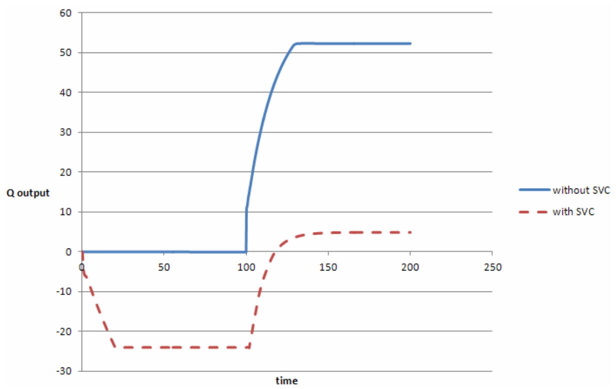


**Fig. 11.** Reactive power of the wind farm

power reserves. When a contingency occurs, the converter of the wind generator operates for reactive control. With a severe contingency in the grid, the converter can be damaged because of the limits of the converter. If the wind farm participates in HSVC, the burden of the converter decreases by cooperating with other generator. Following the results is the result from the aspect of wind generator.

Fig. 11 shows the Q output of the wind farm when the second contingency occurs. For the case in which HSVC is not used, the wind farms operates in the 'constant V mode' to maintain the voltage of the POI. Because of the increasing Q loads, the voltage of the POI decreases, and the Q output increases to control it. Above the result in Fig. 11, the wind generator causes a severe Q output owing to the severe contingency. Therefore, the burden of the converter increases. With HSVC, the burden of the converter decreases because of coordination between the other control generators. In addition, the voltage of the POI can also maintain an adequate value by controlling the pilot bus that represents the voltage control area containing the POI bus.

## 6. Conclusion

Existing wind generators did not affect the stability of the power systems largely because the penetration of wind farms was small. However, wind generators need to secure reactive control capability, like the conventional generators, because the capacity of wind power is increasing. This paper focuses on a reactive power and voltage control method among the various control methods by proposing HSVC combined with large-scale wind farms and synchronous generators. With HSVC, the burden of the converter decreases owing to coordination between each generator. Although the reactive power capability of the wind generator decreases in comparison to the synchronous generator, the wind generator has a margin of reactive power reserve because of HSVC. Further, the voltage of the POI can also be maintained at an adequate value by controlling the pilot bus that represents the voltage control area containing the POI bus. In aspect of system, the HSVC can secure the stability of the power system by preventing the disconnection of large-scale wind farms by limiting the reactive power output. The simulation results for the Jeju power system clearly demonstrate that this control scheme is feasible.

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