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제주계통의 전압조정을 위한 MMC-HVDC 시스템 응용

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Application of MMC-HVDC System for Regulating Grid Voltage Based on Jeju Island Power System

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Abstract

This paper presents a control method of the modular multilevel converter - high-voltage direct current (MMC-HVDC) system to regulate grid voltage on the basis of the Jeju Island power system. In this case, the MMC-HVDC system is controlled as a static synchronous compensator (Statcom) to exchange the reactive power with the power grid. The operation of the MMC-HVDC system is verified by using the PSCAD/EMTDC simulation program. The Jeju Island power system is first established on the basis of the parameters and measured data from the real Jeju Island power system. This power system consists of two line-commutated converter - high-voltage direct current (LCC-HVDC) systems, two Statcom systems, wind farms, thermal power plants, transformers, and transmission and distribution lines. The proposed control method is then applied by replacing one LCC-HVDC system with a MMC-HVDC system. Simulation results with and without using the MMC-HVDC system are compared to evaluate the effectiveness of the control method.

Key words: Grid voltage, Jeju island power system, LCC-HVDC, MMC-HVDC, Statcom

1. Introduction

Nowadays, the voltage source converter - high-voltage direct current (VSC-HVDC) has been employed widely to transfer power over long distance between two power systems. Especially, one kind of the VSC-HVDC system is also developed well in recent time, which is called by a modular multilevel converter - high-voltage direct current (MMC-HVDC) system. It has many advantages over the VSC-HVDC system such as low harmonic, high efficiency, high capacity and so on[1]. The structure and operation of the MMC-HVDC system under various conditions have been researched by many authors over the world[2,3,4,5,6,7,8]. However, almost all of the authors only focus on the transfer of the active power but not on the control of the reactive power. The reactive power is often set to zero in the applications. The structure of the MMC-HVDC system contains the capacitors at dc-link side. Moreover, it is able to control the active and reactive powers independently[4,5]. These characteristics are similar to a static synchronous compensator (Statcom) which is used to control the grid voltage at the point of common coupling (PCC)[10,11,12]. It means that the MMC-HVDC system also has ability to regulate the grid voltage at the position where it is connected to.

This paper presents a control method of the MMC-HVDC system to regulate the grid voltage based on the Jeju island power system. It is a combination between the control of the conventional MMC-HVDC system and the Statcom. The MMC-HVDC system has two functions in this case: (i) transferring the active power, (ii) regulating the grid voltage. To apply the control method, one of the

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LCC-HVDC systems will be replaced by a MMC-HVDC system. A comparison in case of with and without using the MMC-HVDC system is performed to confirm the effectiveness of the proposed control method.

2. Reactive power compensation of the Statcom

The basic structure of the Statcom comprises a dc-link capacitor and a dc-ac converter[10,11]. The function of the Statcom is to regulate the grid voltage by generating or consuming the reactive power to or from the power system. The single-line and vector diagrams of the reactive power compensation are shown in Fig. 1. The load is requiring the reactive power from the source. This is the common case in the power system.

From Fig. 1(a), the source and load currents are calculated by

$$i_s = i_l = i_p + ji_q \tag{1}$$

where i_s and i_l are the source and load currents, respectively. i_p and i_q are the active and reactive currents of load.

Assuming that the reactive current of load is compensated by the Statcom as shown in Fig. 1(b), the source and load currents can be rewritten as

$$i_s = i_p \tag{2}$$

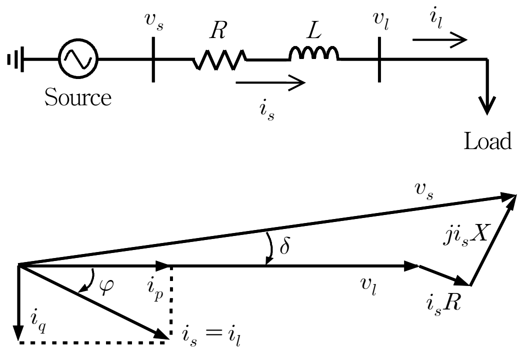
$$i_l = i_p + ji_c \tag{3}$$

where i_c is the compensating current of the Statcom.

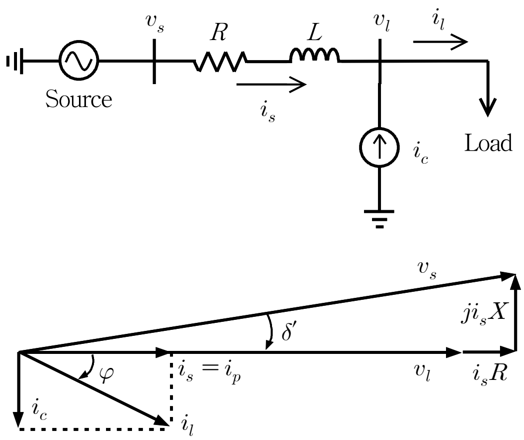
The source current in (2) is smaller than the source current in (1) because there is only one component of the active current. It means that the power losses in the transmission lines and transformers are reduced by using the Statcom. Therefore, the voltage received at the load side will be improved.

3. Ability of exchanging reactive power of the MMC-HVDC system

The MMC-HVDC system is depicted in Fig. 2. It is created by two MMC systems which are connected in back-to-back together. A MMC is constituted by a large amount of sub-modules (SMs) which are arranged in series in arms. Each SM consists of two



(a) without Statcom



(b) with Statcom

Fig. 1. Single-line and vector diagrams of the reactive power compensation.

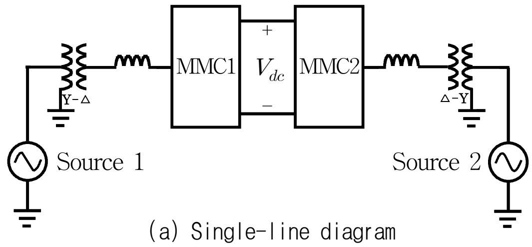
IGBTs, two anti-parallel diodes and a capacitor. Because the use of capacitor in the SM, the MMC-HVDC system will have ability of supporting the reactive power for the power system. This is similar to the dc-link capacitor in the Statcom system[10,11]. From the point of view about the existence of the circulating current in the MMC-HVDC system, the SM capacitance is computed as[9]

$$C = \frac{S}{3.m.N.\omega.\varepsilon.V_c^2}\left[1-\left(\frac{m.\cos\varphi}{2}\right)^2\right]^{\frac{3}{2}} \tag{4}$$

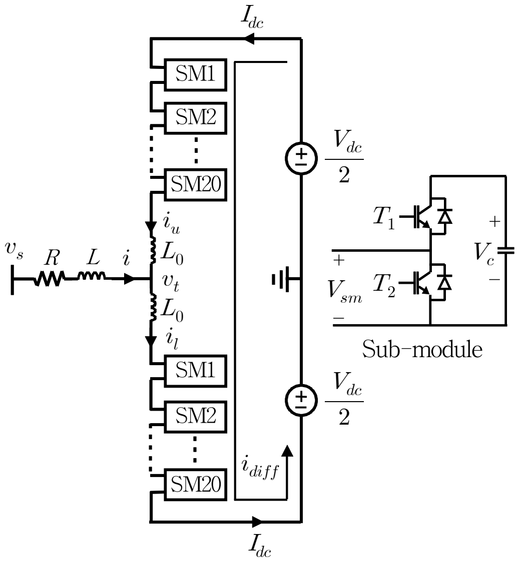
where S is the apparent power of the converter, it is determined by

$$S = \frac{P}{\cos\varphi} = \frac{Q}{\sin\varphi} \tag{5}$$

P and Q are the active and reactive powers. φ is the phase shift between the output voltage and current.



(a) Single-line diagram



(b) Single-phase circuit of the MMC

Fig. 2. The MMC-HVDC system.

$\cos\varphi$ is the power factor. m is the modulation index. N is the number of the SMs per arm. ω is the fundamental frequency. ε is the voltage ripple of the capacitor. V_c is the mean value of the capacitor voltage.

With a certain value of the active power and power factor, the capacity of the capacitor is determined from (4). Then, the reactive power of the MMC-HVDC system will be achieved from (5). In this case, the MMC-HVDC system operates as a source. It not only transfers the active power, but also supplies the reactive power. Moreover, the MMC-HVDC system can control the active and reactive powers independently because it is a type of the voltage source converter. The relationship between the reactive power and the power factor is shown in Fig. 3.

4. Implementation of voltage controller in the MMC-HVDC system

From above analysis, the control of the MMC-HVDC system in this paper is a combination

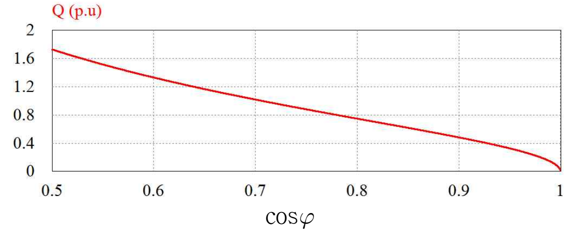


Fig. 3. Relationship between the reactive power and the power factor. P = 1 p.u, $\cos\varphi = 0.5 \sim 1$.

between the control of the Statcom and the conventional control method of the MMC-HVDC system. The MMC-1 is used to control the dc-link voltage and reactive power. The MMC-2 is employed to control the active power and the grid voltage.

The voltages at the ac side derive from Fig. 2 as

$$v_{sk\_x} = i_{k\_x}R + L\frac{di_{k\_x}}{dt} + v_{tk\_x} \tag{6}$$

where k represents for the three-phase components of the voltages or currents, k = a, b, c. x denotes the MMC-1 and MMC-2, x = 1, 2. v_{sk_x}, v_{tk_x} and i_{k_x} are the three-phase voltages and currents of the MMC-x. R and L are the resistance and inductance of the system, respectively.

The ac voltage can be rewritten in the synchronous rotating reference frame by

$$v_{sd\_x} = i_{d\_x}R + L\frac{di_{d\_x}}{dt} + v_{td\_x} - \omega L i_{q\_x} \tag{7}$$

$$v_{sq\_x} = i_{q\_x}R + L\frac{di_{q\_x}}{dt} + v_{tq\_x} + \omega L i_{d\_x} \tag{8}$$

where $v_{sd\_x}, v_{sq\_x}, v_{td\_x}, v_{tq\_x}, i_{d\_x}$ and i_{q_x} denote the dq-axis components of the three-phase voltages and currents of the MMC-x.

The current controllers of the MMC-x will be

$$v^*_{td\_x} = -\left(k_p + k_i\int\right)\left(i^*_{d\_x} - i_{d\_x}\right) + v_{sd\_x} + \omega L i_{q\_x} \tag{9}$$

$$v^*_{tq\_x} = -\left(k_p + k_i\int\right)\left(i^*_{q\_x} - i_{q\_x}\right) + v_{sq\_x} - \omega L i_{d\_x} \tag{10}$$

where the superscript * denotes for the reference value. k_p and k_i are the gains of the proportional-integral controller. $\int$ means the integration of signal.

Because the d-axis component in the synchronous reference frame of the ac voltages is zero, the active and reactive powers of the MMC-x are presented by

$$P_x = \frac{3}{2} v_{sq\_x} . i_{q\_x} \tag{11}$$

$$Q_x = -\frac{3}{2} v_{sq\_x} . i_{d\_x} \tag{12}$$

where P_x and Q_x are the active and reactive powers of the MMC-x.

To monitor the output power of the converter system, the closed-loop control is applied for the power controllers. Therefore, the reference currents are expressed from (11) and (12) as

$$i^*_{q\_2} = \frac{2}{3v_{sq\_2}} \left(k_p + k_i \int\right) \left(P^*_2 - P_2\right) \tag{13}$$

$$i^*_{d\_x} = -\frac{2}{3v_{sq\_x}} \left(k_p + k_i \int\right) \left(Q^*_2 - Q_2\right) \tag{14}$$

To support for the grid voltage, a voltage controller is implemented in the MMC-2 control. From Fig. 2, the voltage drop over the reactance RL is expressed by[13]

$$\begin{aligned} \Delta v &= v_s - v_t \\ &= \frac{RP_2 + XQ_2}{v_s} + j\frac{XP_2 - RQ_2}{v_s} \end{aligned} \tag{15}$$

The imaginary part in (15) is very small in comparing with the real part and almost power systems satisfy with X>>R. Therefore, the voltage drop can be rewritten as

$$\Delta v \approx \frac{XQ_2}{v_s} \tag{16}$$

$$\text{Then } Q_2 \approx \frac{v_s \Delta v}{X} \tag{17}$$

The ac voltage is proportional to the reactive power. Finally, the voltage controller will be described by

$$Q^*_2 = \left(k_p + k_i \int\right) \left(v^*_{sq\_2} - v_{sq\_2}\right) \tag{18}$$

The output signal of the voltage controller is the reference value of the reactive power. Depending on the reference value of the voltage, the MMC-2 will generate or consume the reactive power to or from the power system. Hence, the grid voltage will be stable. The control structure of the MMC-2 system is shown in Fig. 4.

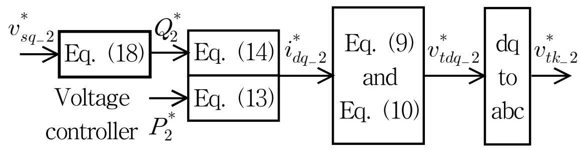


Fig. 4. Control structure of the MMC-2.

5. Overview of the Jeju island power system

The configuration or modeling of the Jeju island power system in the PSCAD/EMTDC simulation program is shown in Fig. 5. It consists of two LCC-HVDC systems, two Statcom systems, wind farms, thermal power plants, transformers, and transmission and distribution lines. The wind farms in Jeju island focus in the east and west sides, thus these wind farms are represented by the 'East Wind Farm' and the 'West Wind Farm'. The main power source in Jeju island is the wind farms that have total installed capacity of 114.645 MW. But the output power of the wind farms is not stable, and it depends on the wind velocity. Thus, the power system needs the support of the thermal power plants and the LCC-HVDC systems which generate both the active and reactive powers. However, the reactive power of the LCC-HVDC systems relates strictly to the active power (it is about 60% of the active power), and it is almost constant. The random change of the load causes the voltage ripple in the power system. This can reduce the lifetime or damage the devices. To solve this problem, the Statcom systems have been installed in the Sinjeju and Halla sub-stations. In the transient condition, the voltage ripple is able to become seriously because the capacity of the Statcom is limited. If the MMC-HVDC system is used in the Jeju island power system, this situation can be improved because it can support amount of variable reactive power, and its response is fast.

6. Simulation results

The Jeju island power system is established by using the PSCAD/EMTDC simulation program as shown in Fig. 5. The parameters of the MMC-HVDC system is given in Table 1.

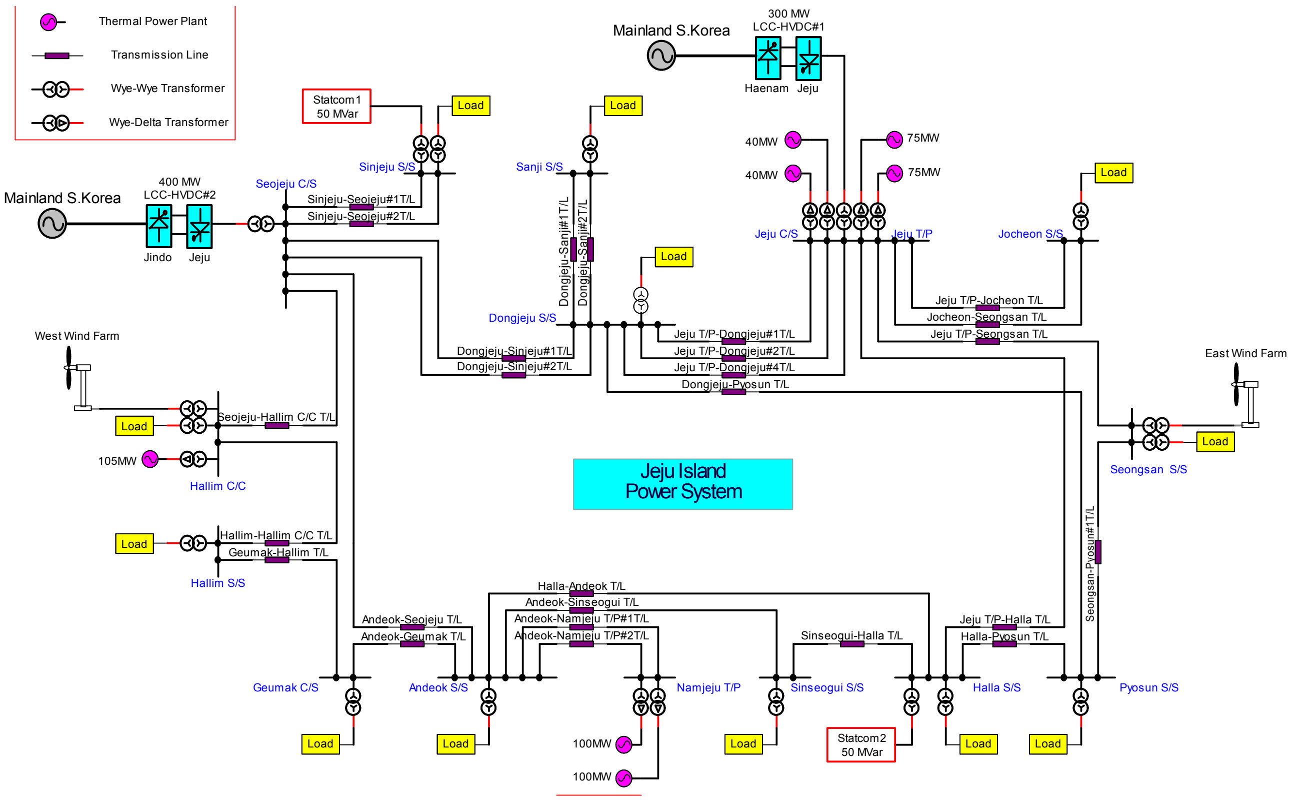


Fig. 5. Modeling of the Jeju island power system.

TABLE I
PARAMETERS OF THE MMC-HVDC SYSTEM

Quantity	Value
Active power	300 [MW]
Reactive power	140 [MVar]
AC system voltage	154 [kV]
Nominal frequency	60 [Hz]
Transformer ratio	160 [kV] / 55 [kV]
DC-link voltage	±50 [kV]
Number of SMs per arm	20
MMC switching frequency	250 [Hz]
Sub-module capacitor	9900 [uF]

Fig. 6 shows the measured results from the real Jeju island power system on 09/18/2013. To get this figure, the measured data from the real Jeju island power system is saved in the ".txt" files. Then, the blocks "File Read" in the PSCAD/EMTDC simulation program are used to read data from these files.

The output power of the wind farms is small and variable during this day as shown in Fig. 6(a). To response sufficiently the load demand, the LCC-HVDC systems transfer the active power from the mainland to the Jeju island power system, and it is almost constant at each time. In this case, the thermal power plants supply the largest power among the power generation sources. The main reactive power source will come from the filters of the LCC-HVDC systems and thermal power plants as described in Fig. 6(b). The Statcom systems are used to stabilize the voltage ripple in the power system. However, the grid voltage is still a small ripple as shown in Fig. 6(c). In this case, the grid voltage is measured at the Jocheon sub-station. At t = 10h46min, the grid voltage has a large oscillation because the LCC-HVDC#2 is activated to supply the power for the system.

Hereinafter, the symbols of the active and reactive powers in figures are defined as follows.

P_Total: Total active power is generated by the wind farms, thermal power plants, LCC-HVDC#1 and LCC-HVDC#2.

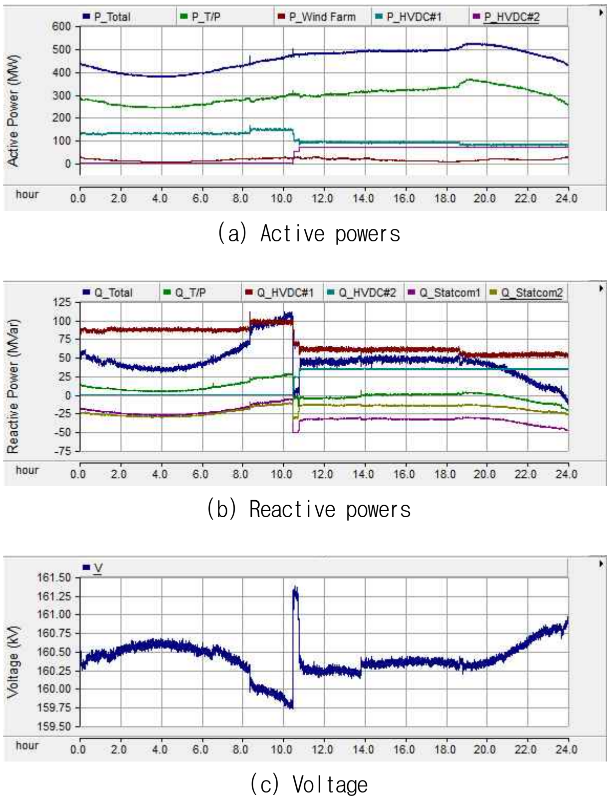
P_T/P: Total active power of the thermal power plants.

P_Wind Farm: Total active power of the wind farms.

P_HVDC#1: Active power of the LCC-HVDC#1.

P_HVDC#2: Active power of the LCC-HVDC#2.

Q_Total: Total reactive power is generated by the

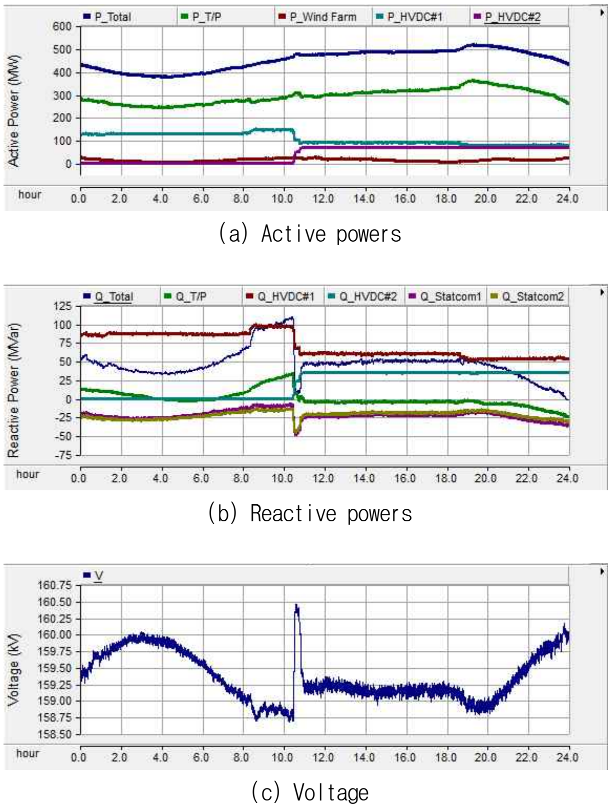


(a) Active powers

(b) Reactive powers

(c) Voltage

Fig. 6. Measured results of the Jeju island power system.



(a) Active powers

(b) Reactive powers

(c) Voltage

Fig. 7. Simulation results of the Jeju island power system.

thermal power plants, LCC-HVDC#1, LCC-HVDC#2, Statcom1 and Statcom2.

Q_T/P: Total reactive power of the thermal power plants.

Q_HVDC#1: Reactive power of the LCC-HVDC#1.

Q_HVDC#2: Reactive power of the LCC-HVDC#2.

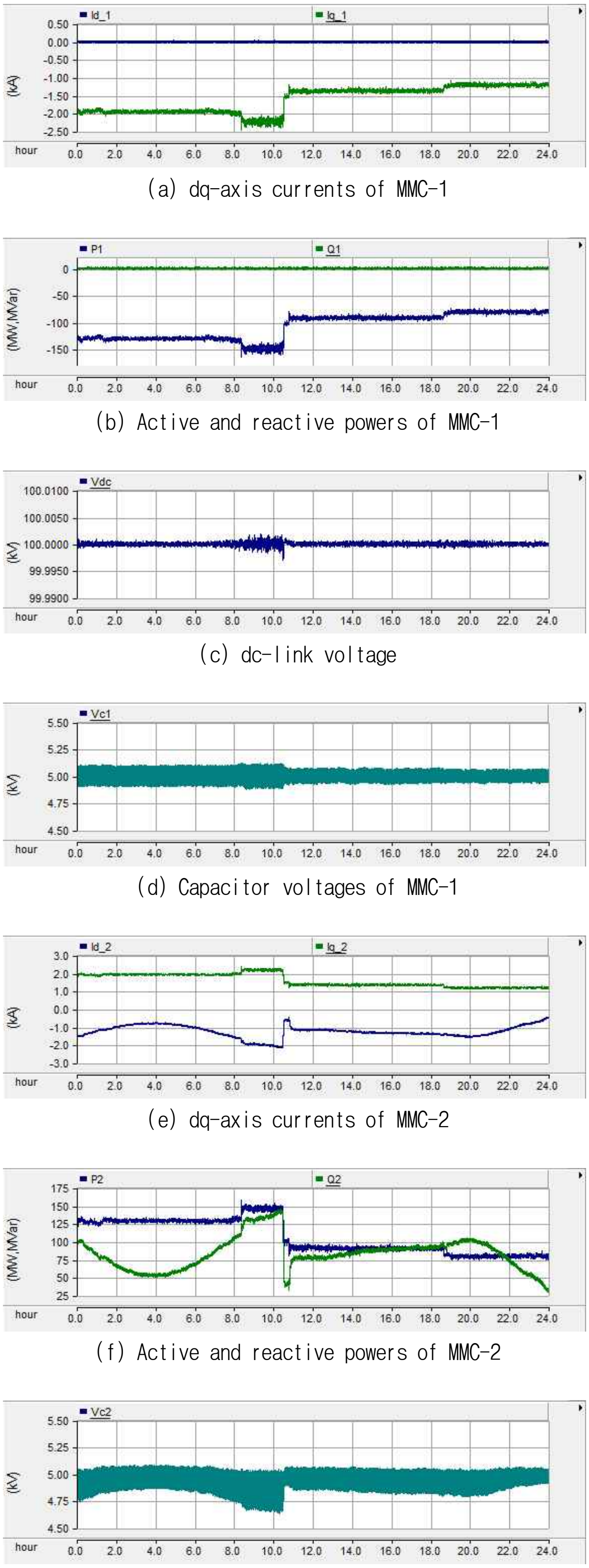
Q_Statcom1: Reactive power of the Statcom1.

Q_Statcom2: Reactive power of the Statcom2.

The simulation results of the Jeju island power system based on the real parameters and measured data are expressed in Fig. 7. It is recognized that the simulation results and the measured data are almost similar. This proves the reliability of the modeling of the Jeju island power system in PSCAD/EMTDC simulation program.

The main purpose of this paper is the operation of the MMC-HVDC system to regulate the grid voltage based on the Jeju island power system. In this study, the LCC-HVDC#1 is replaced by the MMC-HVDC system. The operation of the MMC-HVDC system is shown in Fig. 8. The dq-axis current components of the MMC-1 are expressed in Fig. 8(a). Fig. 8(b) shows the corresponding active and reactive powers. The reactive power is controlled to zero. It means that the MMC-1 is operating at the unit power factor. The active power will depend on the power control in the MMC-2. The dc-link voltage is always kept at its reference value as shown in Fig. 8(c). Fig. 8(d) is the capacitor voltages of the SMs in the MMC-1. It is maintained at their nominal value. The dq-axis current components of the MMC-2 are shown in Fig. 8(e). Fig. 8(f) illustrates the corresponding active and reactive power flows. The reactive power of the MMC-2 is controlled according to the requirement of the new voltage controller. It is not zero in this case. In other words, the MMC-2 is not operating at the unit power factor. The active power is adjusted depending on the power demand of the Jeju island power system. Fig. 8(g) shows the capacitor voltages of the SMs in the MMC-2.

The operation of the Jeju island power system with the MMC-HVDC system is shown in Fig. 9. Comparing with and without using the MMC-HVDC system, it is seen that the active powers in Fig. 9(a) are almost same with the active powers in Fig. 7(a). However, the reactive powers are quite different as shown in Fig. 9(b) and Fig. 7(b). This is because the MMC-HVDC system supplies the reactive power according to the requirement of the grid voltage



(a) dq-axis currents of MMC-1

(b) Active and reactive powers of MMC-1

(c) dc-link voltage

(d) Capacitor voltages of MMC-1

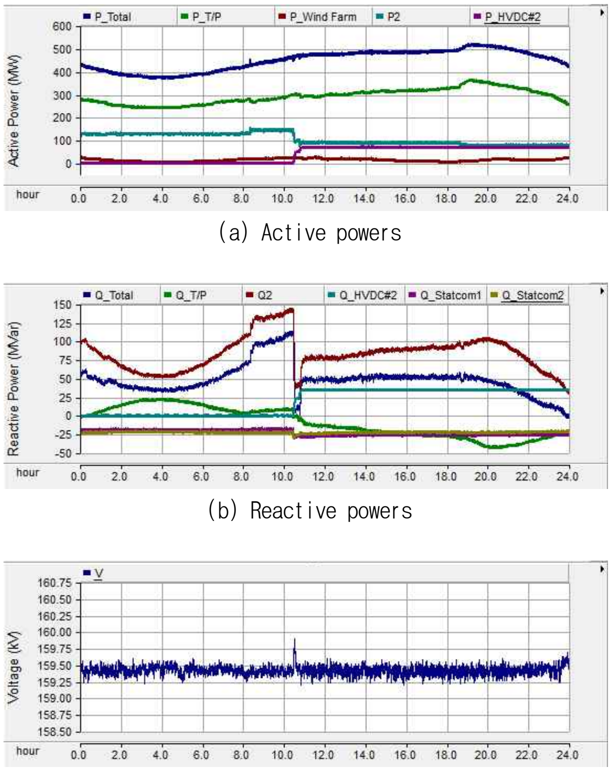
(e) dq-axis currents of MMC-2

(f) Active and reactive powers of MMC-2

(g) Capacitor voltages of MMC-2

Fig. 8. The operation of the MMC-HVDC system.

controller. The reactive powers, which are supplied by the Statcoms, are almost stable. In addition, the peak



(a) Active powers

(b) Reactive powers

(c) Voltage

Fig. 9. The operation of the Jeju island power system with the MMC-HVDC system.

powers of the Statcoms at transient time is also smaller. With the implementation of the voltage controller, the grid voltage is more stable as illustrated in Fig. 9(c) and Fig. 7(c). The peak oscillation of the grid voltage at the transient time is reduced significantly. This points out the effectiveness of the proposed control method. The MMC-HVDC is still operating well while it is supporting for the grid voltage stability.

7. Conclusions and Discussions

This paper has presented a control method of the MMC-HVDC system to regulate the grid voltage based on the Jeju Island power system. The reliability of the modeling of the Jeju island power system in PSCAD/EMTDC software environment has been affirmed. It can operate similarly as the real power system. The simulation results have also demonstrated that the grid voltage is more stable if the MMC-HVDC system is applied to the Jeju island power system. The MMC-HVDC system operates as a Statcom to regulate the grid voltage with the implementation of the voltage controller. In this case, the using efficiency of the MMC-HVDC system is highest. It not only transfers the active power, but also supports for the grid voltage stability.

Because of the rapid development of load demand and wind farms in Jeju island, the Korean government has a plan to build a new HVDC system which can exchange the active power between the mainland and the Jeju island power system. With above analysis, the proposal of using the MMC-HVDC system is quite suitable. Moreover, the installation of a new Statcom is not necessary in this case.

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