J Electr Eng Technol.2015;10(1): 47-55
http://dx.doi.org/10.5370/JEET.2015.10.1.047

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Analyzing Stability of Jeju Island Power System with Modular Multilevel Converter Based HVDC System

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Abstract – This paper proposes the installation of a new modular multilevel converter based high-voltage direct current (MMC-HVDC) system to connect between mainland and Jeju island power systems in Korea in 2020. The purpose is to combine with two old line-commutated converters (LCC)-based HVDC system to achieve a stability of the Jeju island power system. The operation of the overall system will be analyzed in three cases: (i) wind speed is variable, (ii) either one of the LCC-HVDC systems is shutdown because of a fault or overhaul, (iii) a short circuit fault occurs at the mainland side. The effectiveness of the proposed control method is confirmed by the simulation results based on a PSCAD/EMTDC simulation program.

Keywords: Modular multilevel converter, High-voltage direct current, Jeju island power system, Mainland power system, Short circuit fault

1. Introduction

Jeju island has the highest average wind speed among the all promising sites in Korea and it has the best condition for wind power generation. The wind map of Jeju island was shown in [1]. A study on wind speed prediction using artificial neural network at Jeju island in Korea was also investigated by the authors in [2]. It shows that the annual wind speed in the east and west areas of Jeju island is about 7~8 m/s. This is the reason why many companies are investing to build wind farms in these areas. As a result, the total capacity of the wind power generation will be increased in the future. Following the data of the Korean government in the winter in 2020, the maximum demand load in Jeju island is 944 MW. The wind farms can supply up to 500 MW in total capacity of demand load and it is enough to threaten the stable operation of the system because the Jeju island power system is a weak grid. At present, there are two line-commutated converter - high-voltage direct current (LCC-HVDC) systems, HVDC#1 and HVDC#2, connected between the mainland and Jeju island to stabilize the Jeju island power system. In this case, the LCC-HVDC systems operate as a smooth filter and a sub-power supply. However, it only supplies power in one direction, from the mainland to Jeju island. This is no longer suitable in the future when the capacity of the Jeju island power system is over its demand load because of the increase of installed wind power. At that time, there is a demand to transfer power from Jeju island to the mainland. Besides, if the HVDC#2 system is shutdown, the total power that supplies to Jeju island will be smaller than the total load, therefore it needs much more power from the mainland. To overcome this situation, the voltage source converter (VSC) based HVDC system can be used. There are two kinds of VSC: two-level converter and multilevel converter [3-8]. However, the multilevel voltage synthesis strategy is best accommodated to meet the high-voltage level on both ac and dc sides of the VSC-HVDC system [5-7]. The n-level (n>3) diode-clamped converter (DCC) for HVDC applications have been limited because of the complexity in counteracting the dc-capacitor voltage drift phenomenon [8]. This is also the case for multilevel flying-capacitor converter (FCC) topology [6]. Moreover, the DCC and FCC configurations do not fully satisfy scalability, structural modularity, and fault tolerance for HVDC applications. The MMC is a new type of multilevel converter for HVDC applications [9-11]. Basically, the MMC does not have the drawbacks of multilevel and multi-module converters. There were many researches about the basic controls and operations of the MMC in these last years. In [12] and [13], the authors showed out the control strategies for eliminating the circulating currents and maintaining the capacitor voltage balancing of the MMC. The dynamic performances of a MMC-based HVDC system have been analyzed [14]. In [15, 16], the authors presented the control methods of the MMC-HVDC system under unbalanced voltage conditions. It demonstrated that the MMC provides the desired dynamic response under different operating conditions for HVDC applications. Therefore, the MMC is one of the most promising power converter topology for high power applications in the near future, particularly in HVDC links. However, almost all the

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Received: December 13, 2013; Accepted: September 4, 2014

authors only focus on the use of a proportional-integral (PI) current controller when they designed the control strategies for the MMC-HVDC system. If the MMC-HVDC system operates under the unbalanced voltage conditions, this causes some trouble problems because of the complex control of the positive and negative sequence components of the currents in the synchronous rotating reference frame (dq-frame). Recently, a proportional-resonant (PR) current controller has been used [17]. With the PR current controller, the current will be controlled directly in the stationary reference frame (αβ-frame) both balanced and unbalanced voltage conditions. Thus, the complex control of the positive and negative sequence components is not necessary.

This paper proposes the installation of a new MMC-HVDC system for connecting between the mainland and Jeju island power systems in Korea in 2020. The aim is to achieve a stable operation on the Jeju island power system. The control of the MMC-HVDC system will be first analyzed in the αβ-frame. The operation of the overall system will be tested in three cases: (i) wind speed is variable, (ii) either one of the LCC-HVDC systems is shutdown because of a fault or overhaul, (iii) a short circuit fault occurs at the mainland side.

The rest of this paper is organized as follows. The Section 2 introduces the characteristics of the Jeju island power system. Section 3 describes the control method of the MMC-HVDC system. The simulation results are shown in Section 4. Section 5 draws the conclusions.

2. The Characteristics of the Jeju Island Power System

The Jeju island power system has many kinds of power source components such as power generating sources (i.e. thermal power plants, wind power plants, and solar power plants), transmissions, distributions, and HVDC systems. It shows that the possibility of electrical fault is high and it will be increased along with the new installation of renewable energy sources. Hence, the stability of the Jeju island power system will be degraded. As Jeju island to be a free-trade international province, the demand of reliable electric energy sources is urgently increasing. It is not only the problem of energy supply source, but also the power quality is becoming an important issue to meet the expectation of international standard in building the infrastructures. Moreover, since the island is located in a hurricane's path and is known to have frequent lightings, there has been frequent contingencies because of the system heavily depending on HVDC tie lines from the mainland Korea and sporadic variable output from many wind farms located in the east and west sides of Jeju island. At present, two HVDC systems, HVDC#1 with the capacity of 150 MW and HVDC#2 with the capacity of 250 MW, will support for the stabilization of the Jeju island power system. Nevertheless, these HVDC systems only operate in one direction, from the mainland to Jeju island. This will be no longer suitable in the future because the increase of wind power. Thus, the installation of a new HVDC system, HVDC#3, is really necessary, which can operate in bi-direction (i.e., from the mainland to Jeju island and from Jeju island to the mainland) to transfer power between the mainland and the Jeju island power systems.

3. The Control Method of the MMC-HVDC System

The single-line and detail diagrams of the MMC-HVDC system in this paper are depicted in Fig. 1. The system consists of two MMC units connected in back-to-back together. Each MMC has three phase units. A phase unit is structured by two arms in the same leg. Each arm comprises 10 sub-modules (SMs) connected in series and a series inductor which provides current control within the phase arms and limits fault currents. A SM is a half-bridge cell which consists of two IGBTs, two anti-parallel diodes, and one capacitor. The ac side of each MMC is connected to a utility grid via a series-connected resistor and inductor, and a Y/Δ three-phase transformer.

3.1 The current controller

Following Fig. 1(b), the ac voltages can be written by

$$u_{sn\_j} = i_{n\_j}R + L\frac{di_{n\_j}}{dt} + u_{tn\_j} \tag{1}$$

where n means the MMC-1 and MMC-2, n=1,2. j represents for the three-phase components of the voltages or currents, $j=a, b, c$. u_{sn_j}, u_{tn_j} and i_{n_j} are the three-phase voltages and currents of the MMC-n. R and L are the resistance and inductance of the system, respectively.

Transforming (1) into the αβ-frame, we get

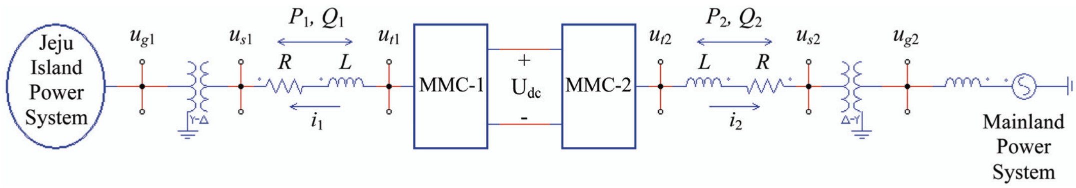
$$u_{sn\_\alpha} = i_{n\_\alpha}R + L\frac{di_{n\_\alpha}}{dt} + u_{tn\_\alpha} \tag{2}$$

$$u_{sn\_\beta} = i_{n\_\beta}R + L\frac{di_{n\_\beta}}{dt} + u_{tn\_\beta} \tag{3}$$

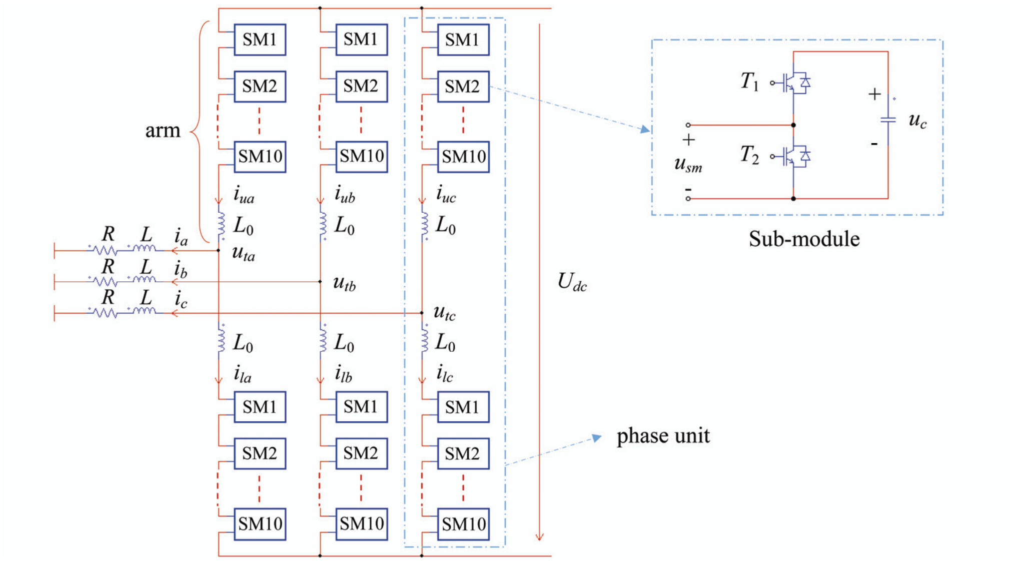
where u_{sn_α}, u_{sn_β}, u_{tn_α}, u_{tn_β}, i_{n_α} and i_{n_β} are the αβ-axis components of the three-phase voltages and currents of the MMC-n.

To compute the PWM voltages, the (2) and (3) are rewritten as

$$u_{tn\_\alpha} = -i_{n\_\alpha}R - L\frac{di_{n\_\alpha}}{dt} + u_{sn\_\alpha} \tag{4}$$



(a)



(b)

Fig. 1. Connecting the MMC-HVDC system between the mainland and Jeju island power systems

$$u_{tn\_\beta} = -i_{n\_\beta}R - L\frac{di_{n\_\beta}}{dt} + u_{sn\_\beta} \tag{5}$$

The current controllers which are used in this paper are the PR current controllers. Therefore, the reference voltages can be described by

$$u^*_{tn\_\alpha} = -G_{PR}\left(i^*_{n\_\alpha} - i_{n\_\alpha}\right) + u_{sn\_\alpha} \tag{6}$$

$$u^*_{tn\_\beta} = -G_{PR}\left(i^*_{n\_\beta} - i_{n\_\beta}\right) + u_{sn\_\beta} \tag{7}$$

where the superscript * represents the reference values of the signals. G_{PR} is the transfer function of the PR current controller:

$$G_{PR} = K_p + \frac{K_i s}{s^2 + \omega^2} \tag{8}$$

where K_p and K_i are the gain of the PR controller. ω is the angular frequency of the system.

3.2 Calculating reference currents

Under the balanced voltage conditions, the voltages and currents of the MMC-n only have the positive sequence component. However, under the unbalanced voltage conditions, the voltages and currents will contain three components: the positive, negative, and zero sequence components. The zero sequence component is removed automatically by using the Y/Δ transformers. With the PR current controller, the three-phase currents are assumed in balancing under the unbalanced voltage condition. It means that the negative sequence component of the currents is zero. Therefore, the active and reactive powers of the MMC-n are expressed by

$$P_n = \frac{3}{2}\left(u^+_{sn\_d}.i_{n\_d} + u^+_{sn\_q}.i_{n\_q}\right) \tag{9}$$

$$Q_n = \frac{3}{2}\left(u^+_{sn\_d}.i_{n\_q} - u^+_{sn\_q}.i_{n\_d}\right) \tag{10}$$

where P_n and Q_n are the active and reactive powers of the MMC-n. $u^+_{sn\_d}$ and $u^+_{sn\_q}$ are the dq-axis components of the voltages in the positive dq-frame.

By using the voltage oriented vector control, the d-axis voltage component of the voltages is zero, $u^+_{sn\_d} = 0$. Hence, the reference currents can be computed from (9) and (10) as

$$i^*_{n\_q} = \frac{2}{3}\frac{P^*_n}{u^+_{sn\_q}} \tag{11}$$

$$i^*_{n\_d} = -\frac{2}{3}\frac{Q^*_n}{u^+_{sn\_q}} \tag{12}$$

It means that the q-axis is used to control the active power and the d-axis is employed to control the reactive power of the MMC-*n*. If the MMC-*n* is used to control the dc-link voltage, the q-axis component of the reference current is replaced by

$$i^*_{n\_q} = \left(K_p + \frac{K_i}{s}\right)\left(U^{*2}_{dc} - U^2_{dc}\right) \quad (13)$$

where U_{dc} is the dc-link voltage.

The dq-axis reference currents will be transformed to the αβ-frame to get the reference currents for the (6) and (7).

The block diagram of the MMC-HVDC system is shown in Fig. 2. If the MMC-*n* is used to control the active and reactive powers, the '*sw*' will be switched to position '1'. If the MMC-*n* is employed to control the dc-link voltage, the '*sw*' will be switched to position '2'.

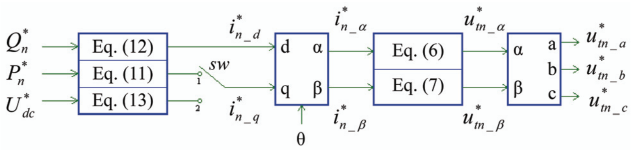


Fig. 2. Block diagram of the proposed control method

4. Simulation Results

The general configuration of the Jeju island power system in 2020 is described in Fig. 3. The power generation will come from wind farms, steam turbines, and two HVDC systems.

$$P_{total} = P_{wind\,farm} + P_{steam\,tubine} + P_{HVDC\#1} + P_{HVDC\#2} \quad (14)$$

The HVDC#1 and HVDC#2 will supply a constant power, meanwhile the main function of the MMC-HVDC

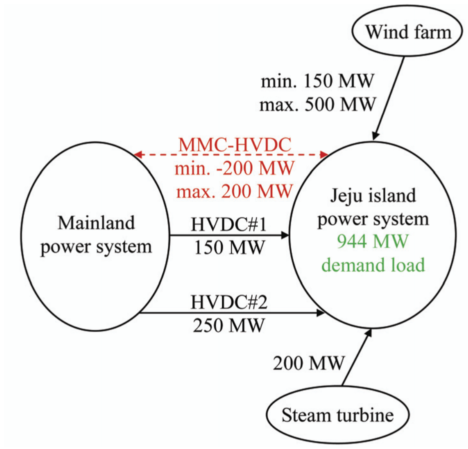


Fig. 3. The general configuration of the Jeju island power system

Table 1. Parameters of the MMC-HVDC system

Quantity	Value
Active power	200 MW
AC system voltage	154 kV
Nominal frequency	60 Hz
Transformer ratio	154 kV/55.1135 kV
dc-link voltage	±50 kV
Number of SMs per arm	10
MMC switching frequency	5 kHz
Sub-module capacitor	3300 μF

is to stabilize for the Jeju island power system in combining with the adjustment of the wind farm output power and demand load. The parameters of the MMC-HVDC system are shown in Table 1. The overall operation of the system will be tested in three cases. In case of faults, this paper only focuses on analysis in the steady-state response but not in the transient response.

The simple model of the Jeju island power system in the PSCAD/EMTDC simulation program is shown in Fig. 4. Because the wind farms almost concentrate on the east and

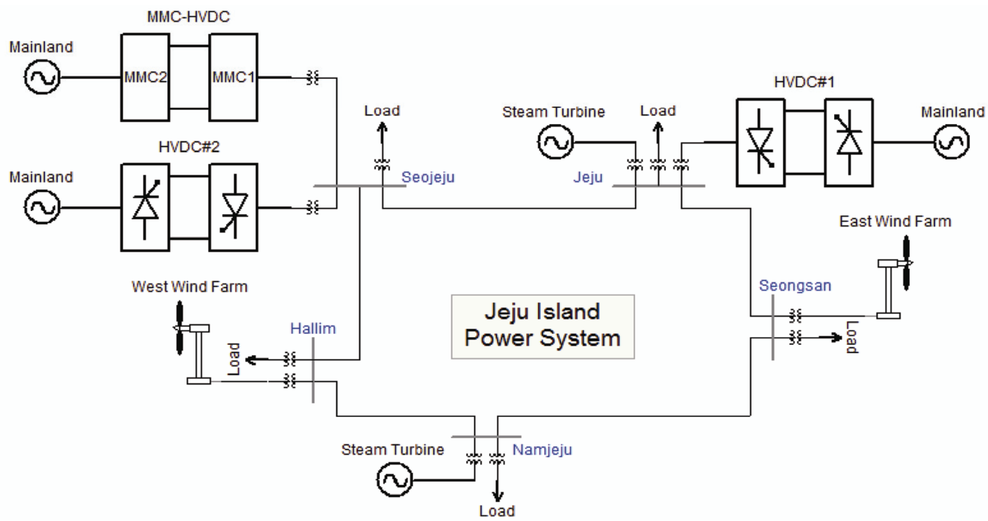


Fig. 4. Simple model of the Jeju island power system in PSCAD

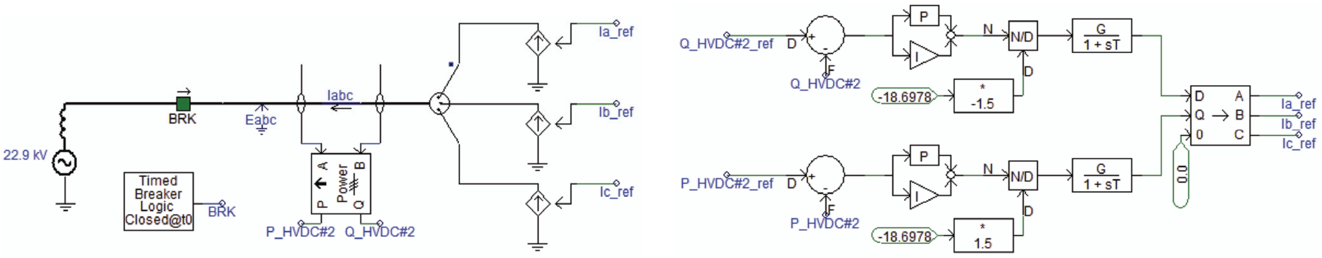


Fig. 5. Model of the HVDC#2

west sides of Jeju island, thus these wind farms are represented by the 'East Wind Farm' and the 'West Wind Farm'. The wind farms, steam turbines, HVDC#1 and HVDC#2 will supply the power to the demand load. In other words, they will inject a three-phase current into the power system in response to the demand current of the load. Therefore, these wind farms, steam turbines, HVDC#1 and HVDC#2 will be modeled by a controlled-current source. Fig. 5 shows the representative model of the HVDC#2. The other ones are similar.

4.1 The variable wind speed

At the normal operation, the powers of steam turbine, HVDC#1, and HVDC#2 are represented in Fig. 6 (a). The most general operation case of the wind farms is its operation under the variable wind speed. In the study case, the output power of the wind farms will be controlled between minimum and maximum values as shown in Fig. 6(b). If the wind farms supply the minimum power of 150 MW, the total of power generation is 750 MW as depicted in Fig. 6(c). This amount of power is less than 944 MW demand load. Thus, the MMC-HVDC system will transfer 944 MW-750 MW=194 MW from the mainland to Jeju island. Similarly, if the output power of wind farms reaches to maximum value of 500 MW, the total of power generation is 1100 MW. In this case, the MMC-HVDC system will transfer 944 MW - 1100 MW = -156 MW from Jeju island to the mainland to make a power balancing on the Jeju island power system. The power and the dc-link voltage of the MMC-HVDC system are shown in Figs. 6(d)-(e), respectively. With the new HVDC system, the power system in Jeju island is always stable at its demand values. The voltage and the frequency of the Jeju island power system is almost constant during operation time as described in Figs. 6(f)-(g).

4.2 The shutdown fault of the HVDC#2

In this study case, the operation of the Jeju island power system is as follows. The wind farms are operating with the output power of 400 MW; the powers from steam turbines, HVDC#1, and HVDC#2 are 200 MW, 150 MW, and 250 MW as shown in Figs. 7(a)-(b). The total of power generation is 1000 MW, meanwhile the demand load is 944 MW as described in Fig. 7(c). Hence, it needs to transfer 944 MW-1000 MW=-56 MW from Jeju island to the mainland. At t =1.1 s, the HVDC#2 is shutdown because of the fault or overhaul. The total of power generation is decreased to 750 MW due to the power of the HVDC#2 is zero. In this case, the Jeju island power system needs to receive 944 MW - 750 MW = 194 MW from the mainland. The power which is transferred by the MMC-HVDC system is shown in Fig. 7(d). Although the HVDC#2 is disconnected suddenly, the dc-link voltage is still kept at its

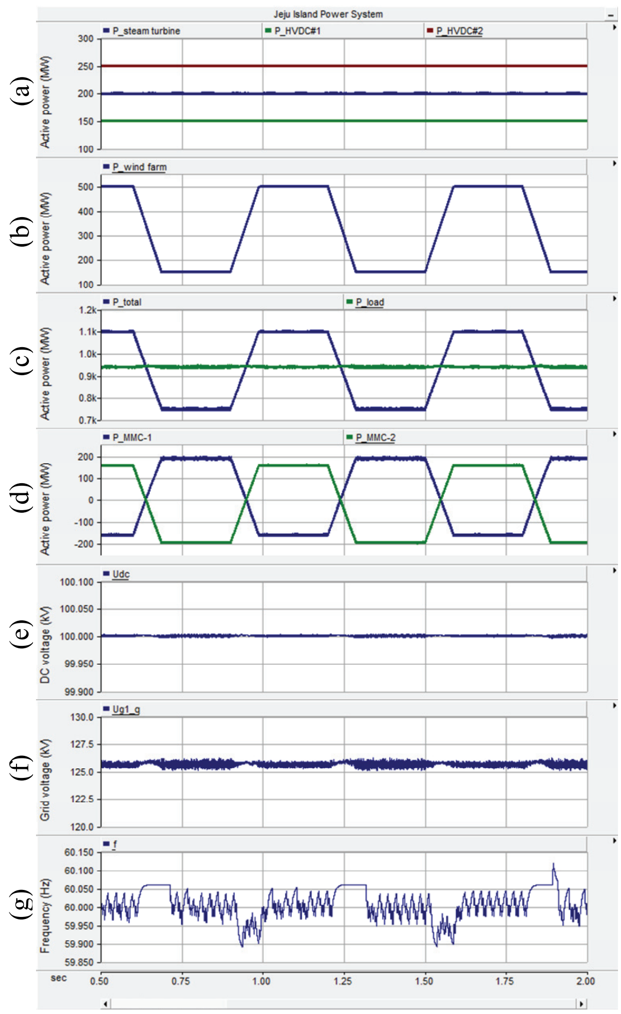


Fig. 6. The operation of the Jeju island power system under the variable wind speed

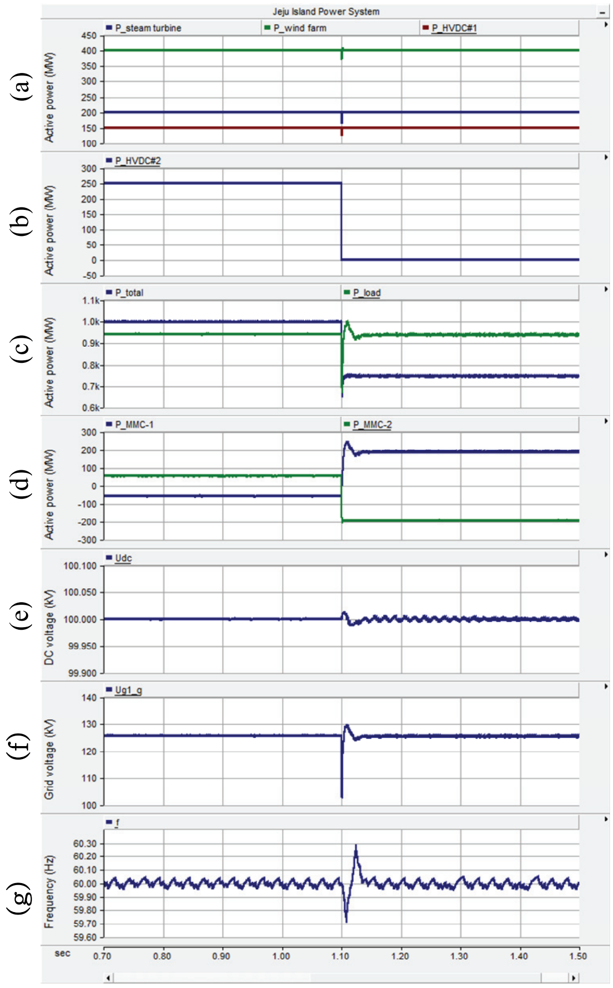


Fig. 7. The operation of the Jeju island power system under the shutdown fault of the HVDC#2

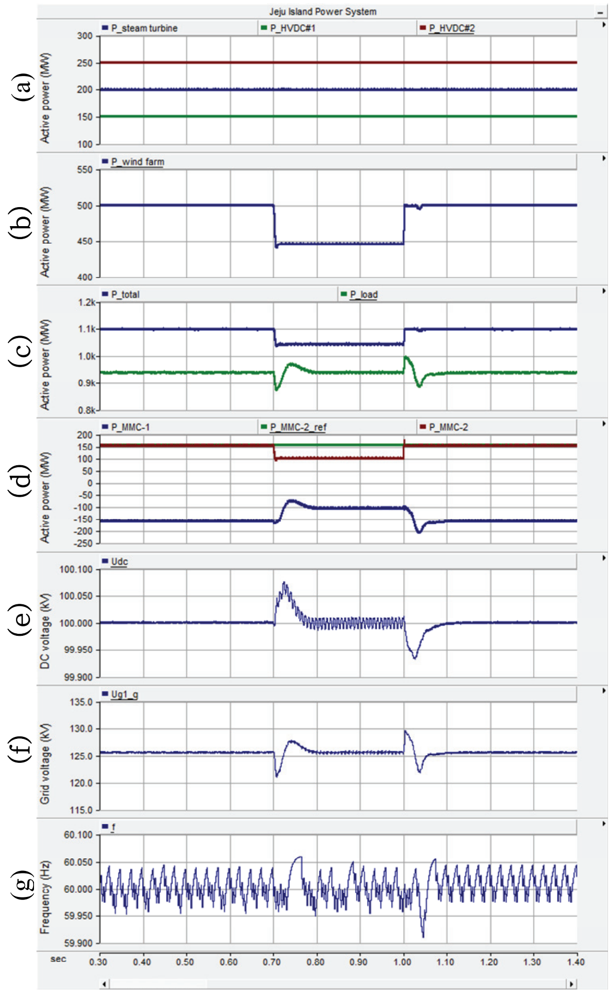


Fig. 8. The operation of the Jeju island power system under the single phase to ground fault - first case

reference value in the steady-state time (Fig. 7(e)). There is an oscillation at the transient response of the ac voltage. However, it is not significant because it only occurs at a very short time as described in Fig. 7(f). Similarly, the frequency of the system is also stable during the shutdown fault of the HVDC#2 (Fig. 7(g)).

4.3 Short circuit fault at the mainland side

In case of single phase to ground fault, the actual power flows through the MMC-HVDC system is always smaller than the nominal power, $P_{MMC\text{-}HVDC\_fault} < P_{MMC\text{-}HVDC\_nom}$. As mentioned in (9), the maximum power can be calculated by

$$P_{n\_\max} = \frac{3}{2} u^{+}_{sn\_q} . i_{n\_q\_\max} \quad (15)$$

If the maximum power is smaller than the reference power, the actual power that transfers through the MMC-HVDC system will be the maximum power. If the maximum power is larger than the reference power, the actual power will follow the reference power.

In the study case, the single phase to ground fault appears at t = 0.7 s and removes at t = 1 s. The power of the steam turbines, HVDC#1, and HVDC#2 is kept at 200 MW, 150 MW, and 250 MW, respectively. The simulation results are carried out in two cases as shown in Fig. 8 and Fig. 9.

First case: In normal operation, when the output power of wind farm achieves maximum value of 500 MW (Fig. 8(b)), the total of power generation on the Jeju island power system is 1100 MW (Fig. 8(c)). It needs to transfer 944 MW - 1100 MW = -156 MW to the mainland by using the MMC-HVDC system (Fig. 8(d)). However, under single phase to ground fault, the MMC-HVDC system can only transfer the maximum power of -105 MW (Fig. 8(d)). Therefore, it remains (-156 MW) - (-105 MW) = -51 MW on the Jeju island power system. This amount of power can cause an overvoltage or losses on the system. To solve this problem, some wind turbines must be turned off with the power of 51 MW (Fig. 8(b)). As a result, the power system is balanced and stabilized as depicted in Figs. 8(c), (f), (g).

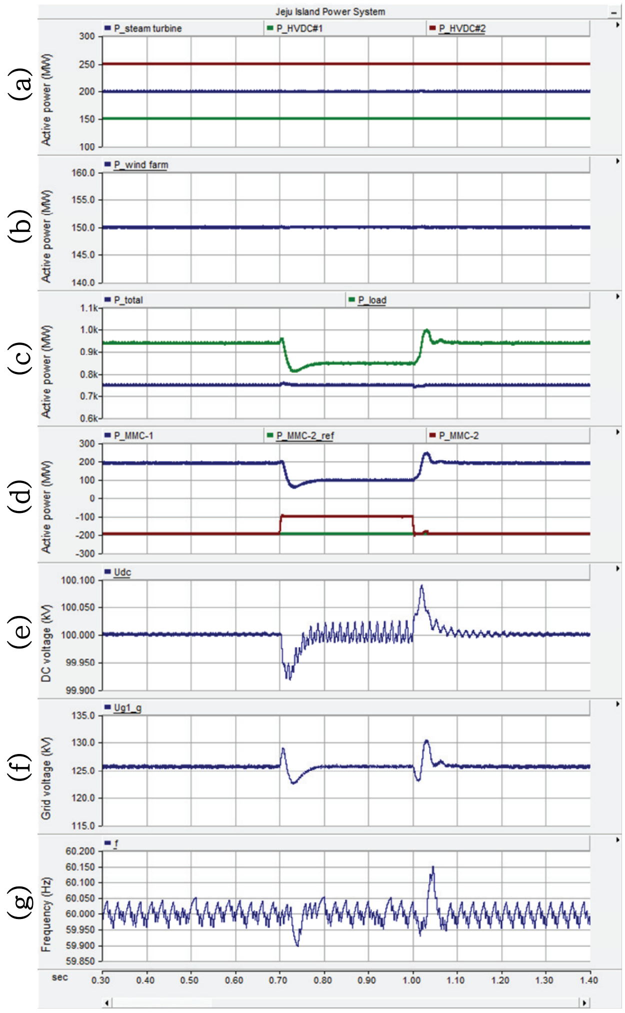


Fig. 9. The operation of the Jeju island power system under the single phase to ground fault - second case

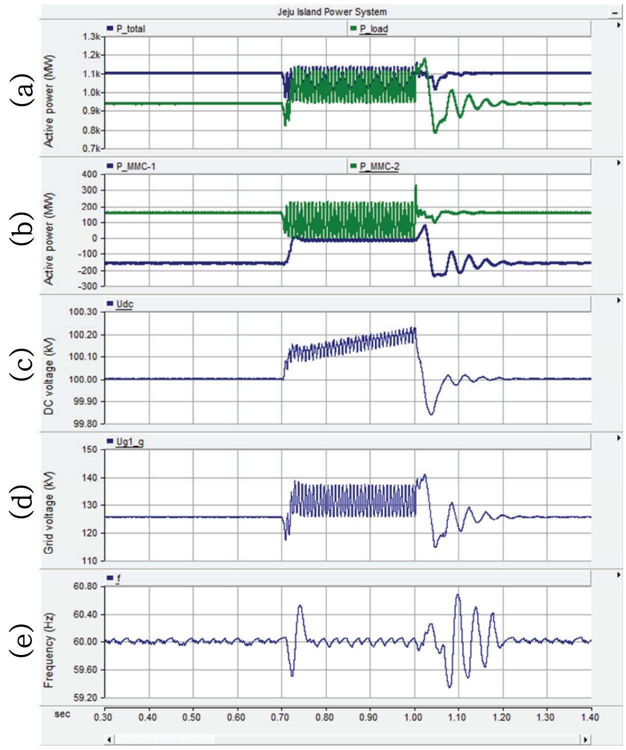


Fig. 10. The operation of the Jeju island power system with the PI current controllers of the MMC-HVDC system

Second case: When the output power of wind farms is minimum 150 MW (Fig. 9(b)), the total of power generation on the Jeju island power system is 750 MW (Fig. 9(c)). To balance the power system, it needs to receive 944 MW - 750 MW = 194 MW from the mainland. However, similar to the first case, the MMC-HVDC system can only transfer the maximum power of 105 MW under the single phase to ground fault. Therefore, the Jeju island power system will be lacked 194 MW - 105 MW = 89 MW. This amount of power can cause a voltage drop or damage to the Jeju island power system. As a result, some loads must be switched off with the power of 89 MW (Fig. 9(c)). Finally, the power system will be stabilized as shown in Figs. 9(c), (f), (g). With these control methods, the Jeju island power system is always kept in balancing state and the system operates with the highest efficiency.

To enhance the PR controller, another simulation is set up in the same operating condition as the first case. However, the current controllers of the MMC-HVDC system in this case are the PI controllers. The simulation results are shown in Fig. 10. With the PI current controllers and without compensating the negative sequence component of the current under the single phase to ground fault, there will be a large oscillation in the power of the MMC-HVDC system as seen in Fig. 10(b). Moreover, the dc-link voltage also increases as shown in Fig. 10(c). As a result, the operation of the Jeju island power system is unstable as illustrated in Figs. 10(a), (d), (e). To protect for the MMC-HVDC system and the power system, the MMC-HVDC system must be disconnected in this case. It means that the operation of the MMC-HVDC system with the PI current controllers is not really reliable under the single phase to ground fault. Meanwhile, the operation of the MMC-HVDC system with the PR current controllers is stable in the same condition as explained in the first case. Thus, the use of the PR controllers for the MMC-HVDC system is reliable in both normal and fault conditions.

5. Conclusions

This paper proposes the installation of a new MMC-HVDC system to connect between the mainland and Jeju island power systems in Korea in 2020. The operation of the MMC-HVDC system and the Jeju island power system has been tested. It demonstrates that the Jeju island power system is always kept stably under normal operation and the shutdown of the HVDC#2 with the MMC-HVDC system. Especially, the MMC-HVDC system still operates reliably under the single phase to ground fault in combining with the control of wind farms and demand load.

Acknowledgements

This work was supported by the Development of 20MW VSC HVDC for offshore wind-farm interconnection of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (*No. 2012T100201551*).

This work was supported by Graduate School of Specialized Wind Energy the Human Resources Development (No.20094020200020) and the Expansion of the Type Testing Site for Wind Turbines (No. 2012T100201731) of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Trade, Industry and Energy.

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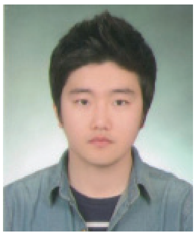

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