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Research paper

An Optimal HVDC Type Study to Increase Wind Power Capacity in Multi-Infeed HVDC Systems

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Abstract

Background/Objectives: The implementation of renewable energy sources such as wind power generators on power system and the use of DC systems that can compensate for unstable characteristics is increasing.
Methods/Statistical analysis: In this paper, interaction factor criteria among buses for voltage stability criteria inertia criteria analysis for frequency stability are introduced in case that several HVDC converter stations are installed close to each other. The method has estimated a system stability analysis including stability, reliability, and interaction based on the generator constraints. To calculate available renewable energy capacity, power balance combination analysis has been performed.
Findings: Conventional methods for analysis of HVDC system input are generally applied to a single infeed HVDC. In this paper, based on the existing analysis method, we analyze the influence of several and various types of HVDCs on the system and propose must-run generator condition to maintain the stability of the system. Furthermore, the effect on wind power penetration limit was analyzed depending on the combination of HVDC system. The superiority of VSC in multi-infeed HVDC system to promote renewable energy implementation could be estimated through the proposed analysis method.
Improvements/Applications: The power system planning and operation including high penetration of renewable energy resources and multi-infeed HVDC system would be performed more appropriately.

***Keywords*:** HVDC, LCC, VSC, multi-infeed, wind penetration.

1. Introduction

Recently, the input ratio of new and renewable energy sources in the power system is rising sharply. These renewable energy sources such as wind and photovoltaic cannot be controlled and have high output variability and can adversely affect the frequency and voltage stability of the power system[1]. Therefore, as the penetration rate of new and renewable energy sources increases, additional facilities should be installed to complement the characteristics[2]. A high voltage AC system and HVDC system are mainly two options for bulk power transmission system. HVDC has various advantages over conventional high voltage AC. It is possible to utilize the line efficiently because there is no skin effect and it is less influenced by problems such as insulation considering the peak value. Accordingly, the number of HVDC transmission systems in the world has been steadily increased, which have been installed in the power system to transmit a large capacity power to the long distant and interconnect the power grid between different countries. etc. The widespread HVDC system creates the multi-infeed HVDC situation that several converter stations locate closely[3,4].

HVDC can be classified into two types, namely, Line Commutated Converter (LCC) type and Voltage Sourced Converter (VSC) type. Both LCC type and VSC type HVDC have advantages such as long distance transmission, asynchronous grid connection, submarine cable use and power control. For long-distance transmissions, a LCC type with a high voltage level and low loss is preferred (eg, 1100 kV Ultra HVDC). Although the VSC type has a disadvantage that the capacity is relatively small, the capacity is rapidly increasing due to the development of the power semiconductor device. VSC HVDCs also support reactive power compensation and black start, and help maintain high power quality. It also has advantages of easy connection with offshore wind power and highly concentrated load areas which has a voltage stability problem and has excellent controllability compared to LCCHVDC. Especially, HVDC is widely used for power transmission in asynchronous connection of independent systems such as European super grid[4]. In this case, high controllability of voltage type enables quick response to changes in power transmission amount rapidly.

In a multi-infeed HVDC system, the influence on the stability may be different depending on the combination of the LCC type and the VSC type HVDC.As mentioned above, LCC HVDCs have reactive power consumption characteristics and VSC HVDCs can absorb or support reactive power, so it is necessary to take into consideration the influences of each other when they are close to each other and their effect on the system[5],[6]. Voltage stability and frequency stability are representative of the stability index of the system. In order to analyze the system in which HVDC and renewable energy sources are installed, it is necessary to change the stability discrimination method of the existing AC system. In this paper, we study the stable operation of multi-infeed HVDC system to simulate a method to improve wind power penetration rate.

2. System Description

A multi-infeed HVDC system refers to a system in which two or more HVDC converters are electrically connected to each other to exchange real (P_{ij}) and reactive power (Q_{ij})between them as shown in Figure 1. Due to electrical connection between HVDC, the voltage ($U_{Ln}\angle\delta_n$) of each converter connecting bus line is influenced by each other, which also affects the DC voltage (U_{dn}) and the DC current (I_{dn}) of the HVDC [7].

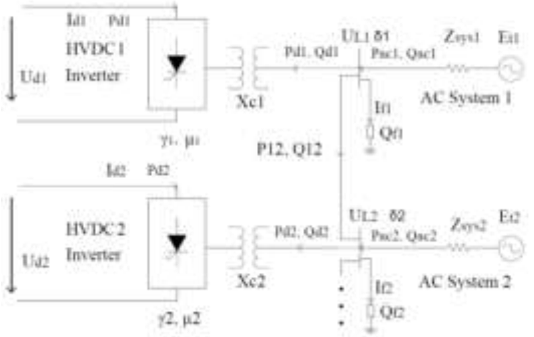
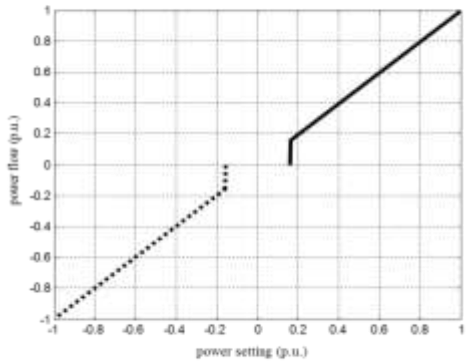


Figure 1: Schematic diagram of the multi-infeed HVDC system

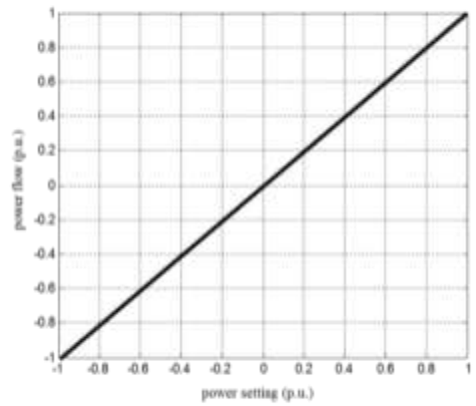
2.1. HVDC type description

The LCC HVDC transmission system is controlled by the firing angle of the thyristor. In other words, since the phase of the alternating current of the converter is always behind the voltage reference, reactive power is absolutely necessary to absorb the lagging current. LCC-HVDC, which normally uses a thyristor, should be supplied by the AC system with ground reactive power equivalent to about 50 to 55% of the direct current transmission. Such reactive power consumption may cause voltage problem as the transmission capacity of HVDC becomes larger. In the case of a strong interconnection system with a high Short Circuit Ratio (SCR), reactive power of capacitors and reactors of an AC filter is generally required to be about 0.6pu of reactive power compensation capability based on a rated 1pu. In particular, the LCC HVDC can control AC voltage through adjustment of the transformer tap and input and removal of the filter according to the amount of electric power. Frequent control of these transformer taps and filters can result in large and small fluctuations in the grid [3].

The VSC HVDC, which can solve the reactive power compensation problem of LCC HVDC transmission system, power flow control performance and quality since semiconductor switching devices that can freely control switching on and off of GTO, IGBT, IGCT, etc. By controlling the phase angle of voltage and current using energy stored in DC capacitor, active and reactive power can be controlled independently. Despite the economics and the converter loss, operation technology for high control performance can support the flexible power system operation. In Figure 2, in case of VSC HVDC, the direction of the power can be controlled by Id control without a separate sequence. DC voltage polarity has not required to be reversed. On the other hand, in the case of the LCC HVDC, there exists a region where the voltage cannot be controlled, typically + 10% to -10%,and has a characteristic in which the direction of electric power is changed through switching of the voltage polarity [3, 4].



(a)



(b)

Figure 2: Power flow by power setting of (a) LCC (b) VSC HVDC

2.2. MIESCR analysis

Short Circuit Ratio (SCR) is criteria that takes into account the strength of the system. When operating an HVDC system with a small Effective Short Circuit Ratio (ESCR) value, the AC voltage of the HVDC converter bus is likely to become unstable status such as overvoltage, under-voltage, or voltage oscillation. Therefore, the possibility of the commutation failure is increased [8].Generally, if the ESCR is greater than 3, it is considered to be connected to the stronger AC system and, if less than 2, to the weaker AC system. ESCR can be expanded and applied to the multi-infeed HVDC system. Multi-Infeed Interaction Factor (MIIF)is a factor indicating how much the other j-th bus voltage when a voltage change occurs on specified i-th bus. The closer the electrical distance between the two buses, the greater the MIIF is obtained.

Multi-Infeed Interaction Factor (MIIF)

$$MIIF_{i,j} = \frac{\Delta V_j}{1\%\ change in V_i} \quad (1)$$

Multi-Infeed Interaction Effective Short Circuit Ratio (MIESCR)

$$MIESCR_i = \frac{SCC_i - Q_{ci}}{P_{di} + \sum_{\substack{j=1 \\ j\neq i}}^{N} P_{dj} \times MIIF_{i,j}} \quad (2)$$

2.3. Effective inertia analysis

The Effective Inertia Constant is the ability to maintain the frequency by the rotational inertia of the AC system [9]. According to IEEE Standard 1204-1997, Hdc is required to be 2.0 or more for stable operation of HVDC. In general, there are the following cases that can cause system frequency reduction. HVDC commutation failure (simultaneous current failures should be considered between buses with a MIIF greater than 0.6), accidents at the HVDC transmission line or front end, and DC line accident. If we suppose to keep the frequency fluctuation within 5% when you supply the system with HVDC due to system accident, which is the harshest situation, and then return from the system accident after 0.2 seconds after all the system is dropped.

$$H_{dc} = \frac{p \times dt \times f_0}{2df} = \frac{1 \times 0.2 \times 1}{2 \times 0.05} = 2$$

$$= \frac{MVA\ rating\ of\ the\ machine}{MW\ rating\ of\ the\ dc\ system} \quad (3)$$

3. Simulation

3.1. Target system

As shown in Figure 3, #1 HVDC transmission system was installed between Haenam and Jeju island in 1998, which is the first HVDC system furnished in Korea. and has been operated. The construction of additional HVDC transmission system between mainland and the Jeju island has been currently underway to cope with recent changes of the power market of the Jeju island, for examples the increase of power demand and the capacity of wind power generation. etc. #2 HVDC transmission system construction completed in 2014 and #3 HVDC will be installed in near future. The Jeju power system will be operated with multi-infeed HVDC system connected to mainland power system[10]. In Figure 4, #1 HVDC is for unidirectional power flow from mainland to Jeju island. #2 HVDC has a Simultaneous Bidirectional Power Flow Control (SBPFC) functionality and support reversal power flow from Jeju island to mainland. #3 HVDC is assumed that would be LCC type with an SBPFC functionality or VSC type which has continuous operating area.

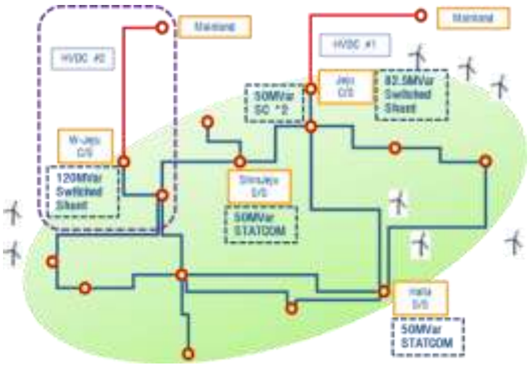


Figure 3: Schematic diagram of Jeju island

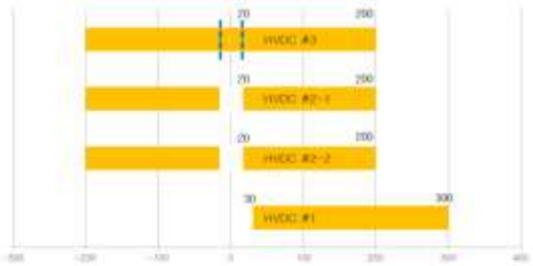


Figure 4: Operating region of Jeju HVDC systems

Table 1 summarizes the MIIF at off peak load and peak load of Jeju system. In general, MIIF appears larger at off-peak loads and smaller at peak loads. In this study, MIESCR was considered based on the higher values of MIIF in more severe conditions, ie, the Jeju C/S and Jeju C/S buses. In the MIESCR review, the scenario of the generator operation was considered from case 1 where only Jeju internal combustion engine starts to case 9 which is the case of all generator startup scenario. The MIESCR review was conducted for 400MW and 200MW based on 600MW of maximum HVDC operation.

Table 1: Power system information for Jeju island

	Peak Case		Off-Peak Case	
	Jeju C/S	Seojeju C/S	Jeju C/S	Seojeju C/S
Voltage fluctuation	1	1.0003	1	1.01167
	0.99	0.9924	0.99	1.0031
$MIIF_{jeju,\ seojeju}$	0.79		0.857	
Voltage fluctuation	1.0147	1	1.0203	1
	1.0079	0.99	1.0115	0.99
$MIIF_{seojeju,\ jeju}$	0.68		0.88	

The must-run generator scenario in Jeju power system can be organized as shown in Table 2. Depending on the combination of generators that are turned on, the short circuit capacity of the entire system also changes. As shown in Table 2, if the generator with high MVA rating is turned on a lot, the short circuit capacity of the system also becomes large.

Table 2: Jeju system generator must-run scenario and short circuit capacity

Gen	Rating	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
Jeju DP#1	40	ON	ON	ON	ON	ON	ON	ON	ON	ON
Jeju DP#2	40	ON			ON	ON	ON	ON	ON	ON
S-Jeju TP#3	100		ON		ON		ON	ON	ON	ON
S-Jeju TP#4	100						ON		ON	ON
Jeju TP#2	75			ON		ON		ON	ON	ON
Jeju TP#3	75									ON
$SCC_{Jeju\ C/S}$ [MVA]		586.99	916.14	838.3	1018.6	941.3	1268.9	1371.2	1618.9	1958.9
$SCC_{SeoJeju}$ [MVA]		528.59	876	725.42	957.66	800.48	1239	1218.5	1497.7	1714.3

HVDC # 1 and # 2 operation points were used as existing operation points (#1 : 150MW, #2 : 250MW) and HVDC # 3 200MW operation condition was examined. In case of LCC HVDC installation, MIESCR condition was satisfied from Case 8, and MIESCR condition was satisfied from Case 4 in case of VSC HVDC installation as shown in Table 3. In other words, it means that the Jeju system including multi-infeed HVDC system can be operated stably if the must-run generator that satisfies the minimum MIESCR value required for each type is turned on.

Since the HVDC can supply more than 90% of off-peak to 600MW out of the total 757MW load at the peak after the # 3 HVDC injection after the # 3 HVDC injection, there is a margin to the inertia constant and the standard value recommended by the IEEE 2.0 Respectively. In conclusion, Case 1 and Case 3 violate the conditions as shown in Table 4. In order to keep the frequency of the system stable, the must run generator must be turned on more than the scenario.

Table 3: MIESCR depending on the HVDC type

MIESCR_LCC	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
Jeju C/S	0.6652	1.2569	1.1151	1.4322	1.2923	1.9875	2.0594	2.6144	3.2509
SeoJeju C/S	0.6904	1.3268	1.0599	1.4738	1.1944	2.0844	1.9576	2.5524	2.974

MIESCR_VSC	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
Jeju C/S	1.349	2.2606	2.0422	2.5307	2.3152	3.3862	3.497	4.3519	5.3324
SeoJeju C/S	1.0031	1.9275	1.5397	2.1411	1.7353	3.0282	2.8439	3.708	4.3205

Table 4: Effective inertia depending on generator must-run scenario

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
H_{ac}	961.76	1430.98	1184.21	1732.66	1485.89	2503.56	2256.79	3027.69	3551.81
H_{dc}	1.60	2.38	1.97	2.89	2.48	4.17	3.76	5.05	5.92

3.2. Wind power penetration limit

All of the above considerations were carried out in consideration of various HVDC operating conditions. As a result of examining the MIESCR and the effective inertia constant condition, when the HVDC 3 phase is put into the LCC HVDC, the peak load (757MW) is operated with the generator condition of Case 8 or more under the maximum operating condition. However, in case of the VSC HVDC, there is no violation in the above two examinations from Case 4 and above, and it can be said that stable operation is possible in Case 2 considering the self-voltage control ability of the VSC type.

$$P_{gen.must} = Max(Gen_{escr}, Gen_{hdc}) \quad (4)$$

Based on the above reviews, the wind power threshold can be defined by must-run generator constraints. In case of HVDC 1, only uni-directional transmission from land to Jeju is considered. In case of Units 2 and 3, Automatic Frequency Control (AFC), SBPFC. It is assumed that the operation area is bidirectional maximum 200 MW. Wind power generation fluctuation, and Jeju system accident problem. However, HVDC can cope with HVDC easily because HVDC can perform high frequency operation in the entire operation range of -370MW ~ 600MW. As shown in Table 5, an available wind power generation capacity can be estimated by power balance of the system using equation (5) and (6) [11].

$$P_{load} = P_{dc\#1} + P_{dc\#2} + P_{gen.must} + P_{wind} + P_{dc\#3} \quad (5)$$

$$P_{wind} = P_{load} - \sum P_{dc} - P_{gen.must} \quad (6)$$

Table 5 : Wind capacity growth prediction for Jeju island

Gen	Rating	LCC(Case4)	VSC(Case8)
Jeju DP#1	40	ON	ON
Jeju DP#2	40	ON	ON
S-Jeju TP#3	100	ON	ON
S-Jeju TP#4	100		ON
Jeju TP#2	75		ON
Jeju TP#3	75		
$P_{gen.must}$		60	140
$P_{wind.peak}$		1067	987
$P_{wind.offpeak}$		703	623

4. Conclusion

In this paper, the modeling of the HVDC system in Jeju island which can reflect stability constraints is performed. An analysis method and operation strategy for the stable operation of different types of multi-infeed HVDC power system is proposed. Based on the propose method, the optimal operation strategies of the multi-infeed HVDC system between the mainland of Korea and the Jeju are suggested to ensure the stability of the Jeju island power system. In the study, simulation results show that VSC HVDC requires fewer must-run generator compared to LCC HVDC. Therefore, VSC HVDC can promote more renewable energy implementation to balance power supply and demand. In the future, an economic comparison and optimal operation point selection for the several objectives can be performed based on the result.

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