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Improvement of LCC-HVDC Input-Output Characteristics using a VSC-MMC Structure

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〈Abstract〉

High voltage direct current(HVDC) systems has been an alternative method of a power transmission to replace high voltage alternate current(HVAC), which is a traditional AC transmission method. Due to technical limitations, Line commutate converter HVDC(LCC-HVDC) was mainly used. However, result from many structural problems of LCC-HVDC, the voltage source converter HVDC(VSC-HVDC) are studied and applied recently. In this paper, after analyzing the reactive power and output voltage ripple, which are the main problems of LCC-HVDC, the characteristics of each HVDC are summarized. Based on this result, a new LCC-HVDC structure is proposed by combining LCC-HVDC with the MMC structure, which is a representative VSC-HVDC topology. The proposed structure generates lower reactive power than the conventional method, and greatly reduces the 12th harmonic, a major component of output voltage ripple. In addition, it can be easily applied to the already installed LCC-HVDC. When the proposed method is applied, the control of the reactive power compensator becomes unnecessary, and there is an advantage that the cut-off frequency of the output DC filter can be designed smaller. The validity of the proposed LCC-HVDC is verified through simulation and experiments.

Keywords : LCC-HVDC, VSC-HVDC, Modular Multi-level Converter(MMC), Power Factor Correction(PFC), 3-Phase Thyristor Rectifier

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1. Introduction

High voltage direct current(HVDC) system is divided into current type HVDC (LCC-HVDC) and voltage type HVDC (VSC-HVDC). LCC-HVDC uses a thyristor to control the turn-on time of the delay angle α, but since the turn-off of the switch is impossible, reactive power is generated on the input side and control response is slow[1-2]. VSC-HVDC uses an IGBT that can turn on/off, so it has fast control response and can control reactive power. For this reason, recently, research on VSC-HVDC has been actively conducted[3]. However, VSC-HVDC has a limited capacity of up to 2GW, so it is difficult to apply to a large-scale system. And, it is expensive, and the loss is relatively large compared to LCC-HVDC[4-5]. Therefore, a study on a new type HVDC system that can improve the stability and control performance of the conventional LCC-HVDC is needed [6].

In this paper, the characteristics of LCC-HVDC are analyzed and the advantages and disadvantages of each method are summarized. In addition, we propose a new HVDC system that can reduce the power factor and output voltage ripple by connecting multiple sub converters of MMC structure to the conventional 12-pulse thyristor rectifier in series. Since the performance and reliability of the system can be increased by adding serial auxiliary converters to the previously installed LCC-HVDC, it has the advantage of not requiring a lot of cost and additional equipment. Finally, the feasibility of the proposed method is verified through simulations and experiments.

2. LCC-HVDC

2.1 3-Phase thyristor rectifier

Figure 1 shows the circuit of LCC-HVDC.

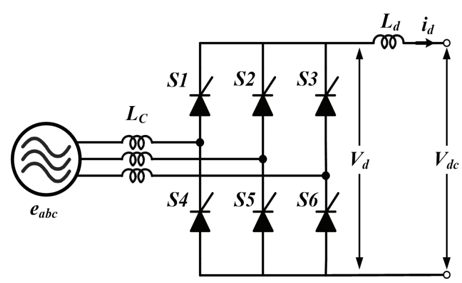


Fig. 1 3-Phase thyristor rectifier

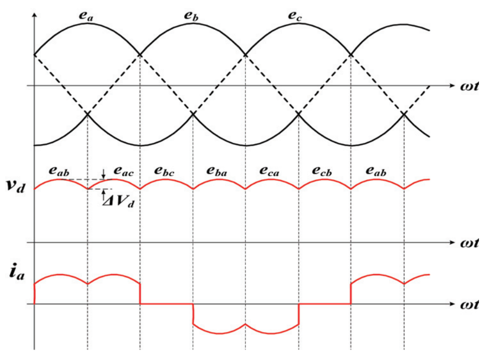
The analysis of LCC-HVDC is the same as 3-phase thyristor rectifier. The phase voltage of 3-phase input power is expressed as

$$\begin{aligned} e_a &= E_m\cos(\omega t - 60^\circ) \\ e_b &= E_m\cos(\omega t - 180^\circ) \\ e_c &= E_m\cos(\omega t + 60^\circ) \end{aligned} \quad (1)$$

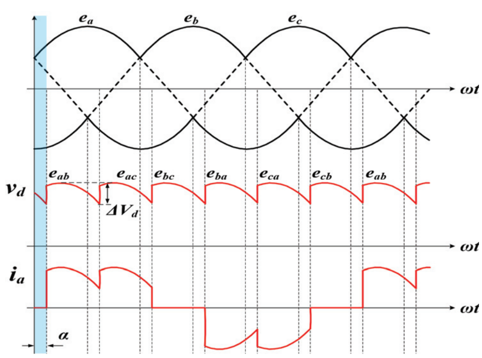
where E_m is the maximum value of the phase voltage. And, the line voltage is expressed as

$$\begin{aligned} e_{ac} &= e_a - e_c = \sqrt{3}E_m\cos(\omega t - 90^\circ) \\ e_{ba} &= e_b - e_a = \sqrt{3}E_m\cos(\omega t + 150^\circ) \\ e_{cb} &= e_c - e_b = \sqrt{3}E_m\cos(\omega t + 30^\circ) \end{aligned} \quad (2)$$

Figure 2(a) shows the voltage and current waveforms for equations (1) and (2). To simplify the analysis, it is assumed that the power inductance is negligible(L_c=0) and there is no the delay angle. The rectifier output voltage v_d consists of 60° components of the line voltage. Therefore, the average output voltage can be obtained by integrating for an arbitrary 60° section. When ωt is denoted by θ and considering the interval between 0° and 60°, the average output voltage without α is expressed as



(a) α = 0°



(b) 60° ≥ α 〉0°

Fig. 2 Voltage and currents of a 3-phase thyristor rectifier

$$V_{d(\alpha=0)} = \frac{3}{\pi}\int_0^{60} e_{ab}\,d\theta = \frac{3}{\pi}\int_0^{60} \sqrt{3}E_m\cos(\theta-30^\circ)\,d\theta = 1.65E_m \quad (3)$$

Here, considering the delay angle α, Equation (3) is changed as

$$V_d = \frac{3}{\pi}\int_{\alpha}^{60+\alpha} e_{ac}\,d\theta \quad (4)$$

Then, the average output voltage according to the delay angle of the thyristor rectifier can be defined as

$$V_d = V_{d(\alpha=0)}\cos\alpha = 1.65E_m\cos\alpha \quad (5)$$

Therefore, it can be seen that the average output voltage decreases as α increases, and, the output voltage ripple increases. Fourier analysis of the output voltage of an ideal three-phase thyristor rectifier contains 6th harmonics (6th, 12th, 18th, 24th, 30th, etc.). Delay angle α has a significant influence on the harmonic voltage magnitude. Figure 2(b) shows the output voltage and input phase current according to α. It can be seen that the output voltage ripple increases according to α, and it can be inferred that the input power factor decreases because the phase difference by α increases compared to the phase current in Figure. 2(a).

Figure 3 shows the change in reactive power according to active power and α. It can be seen that the reactive power increases as the active power increases, and the slope of the graph increases as α increases.

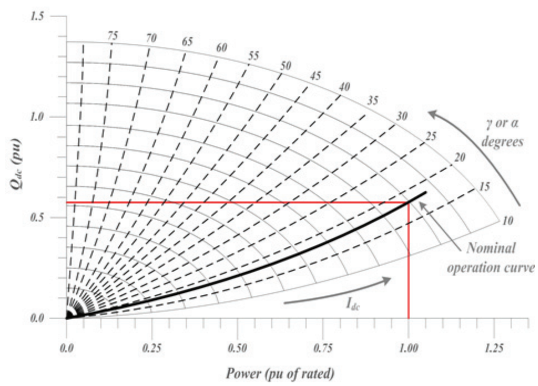


Fig. 3 Reactive power characteristic according to active power and α

2.2 The conventional LCC-HVDC and VSC-HVDC

Figure 4 shows the Modular Multilevel Converter(MMC) structure of a typical VSC-HVDC. The MMC has a structure in which several sub-modules are connected in series. The MMC can increase the switching frequency, so the control response is faster than a three-phase thyristor rectifier that controls α every 60° of the fundamental frequency. In addition, there is an advantage of being able to control the reactive power. However, MMC has a circulating current in each arm which is caused by the difference between the DC link voltage and the capacitor voltage of the entire sub-module.

Table 1 shows the advantages and disadvantages of LCC-HVDC and VSC-HVDC.

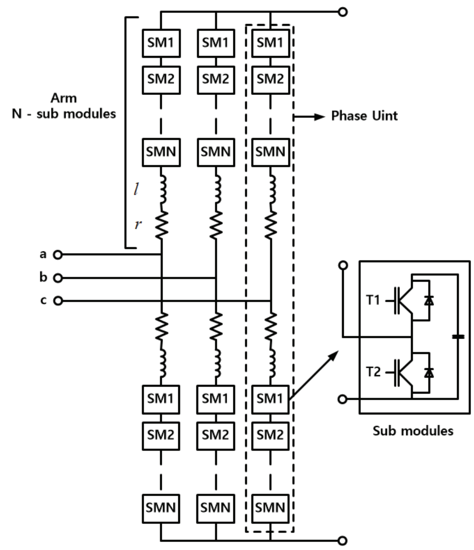


Fig. 4 The MMC structure of VSC-HVDC.

Table 1. Comparison of LCC-HVDC and VSC-HVDC.

LCC	- High efficiency. - Reactive power compensation equipment required. - large installation area. - Slow response. - Many requirements for power transmission.
VSC	- Low efficiency. - The power capability is limited. - Reactive power control available. - Small installation area. - Fast response. - Multi-terminal available. - Black-start available. - High installation cost.

LCC-HVDC is a technology that has been proven by commercial operation for a long time, and most currently installed HVDC is LCC-HVDC. Recently, there is a trend to change to a VSC-HVDC due to various disadvantages of LCC-HVDC as shown in

Table 1. However, it is impossible to replace the already installed LCC-HVDC with VSC-HVDC because of the cost. Therefore, in this paper, we propose a new type of HVDC system that can improve the stability and control performance of the conventional LCC-HVDC.

3. The proposed LCC-HVDC

Figure 5 shows the structure of the new LCC-HVDC combined with the proposed MMC structure. A 12-pulse rectifier is adopted to reduce reactive power, and the auxiliary converter of the MMC structure connected in series with the conventional 12-pulse rectifier receives the output voltage of the rectifier, and then controls the output voltage V_{dc}. Figure 6 shows the principle of the proposed method. The output voltage V_{dc} is made by synthesizing the voltage of the serial auxiliary converter composed of sub-modules with LCC-HVDC voltage having a ripple of 12 times the fundamental frequency.

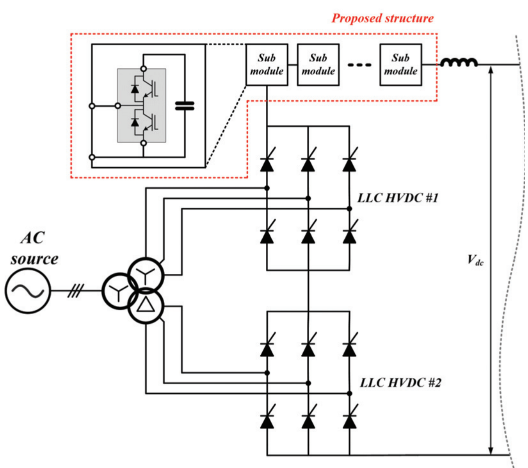


Fig. 5 The proposed LCC-HVDC using the MMC structure

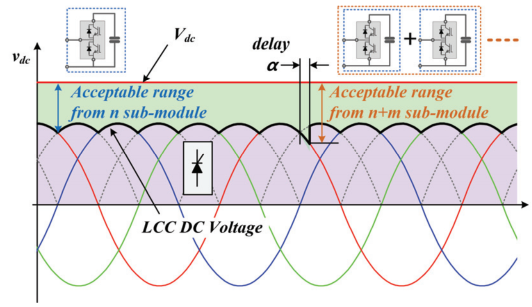


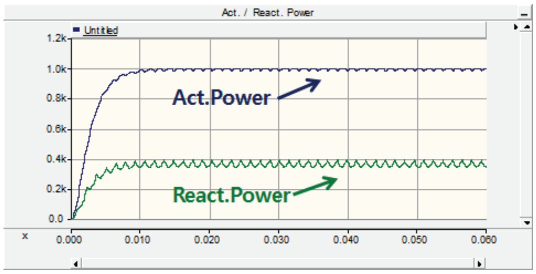
Fig. 6 Principle of the proposed system

The series auxiliary converter(one VSC - MMC) controls V_{dc} to cancel the ripple. As α increases, the voltage range of the auxiliary converter become higher, so the number of sub-modules must be increased. And, as the number of serial auxiliary converters increases, the output ripple can be effectively reduced. For this reason, α can be maintained at a constant value, and when it is maintained at a small value, the reactive power can be greatly reduced, and the control of the reactive power compensation facility becomes unnecessary.

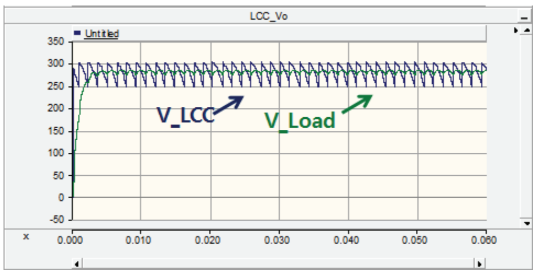
4. Result of simulation and experiment

4.1 Simulation

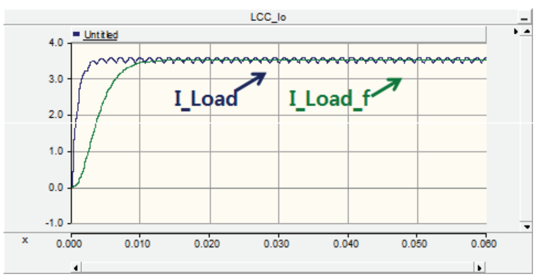
Figure 7 shows the LCC-HVDC simulation



(a) Input power



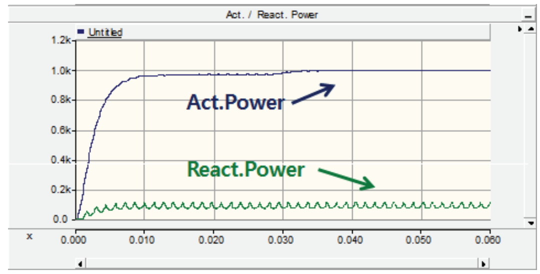
(b) Output voltage



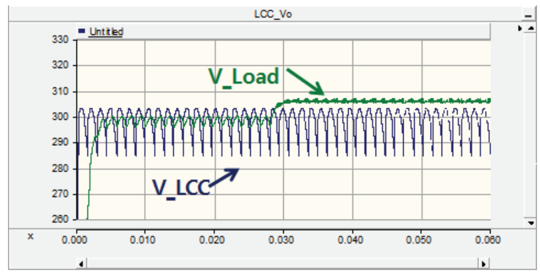
(c) Output currents

Fig. 7 Voltage and currents of conventional LCC-HVDC. (1000[MW] / α=20[°])

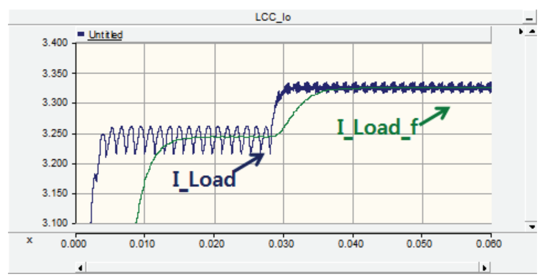
results under the condition of 1000 [MW] and α of 20° . Reactive power of about 350 [MW] is generated, and it can be seen that there is a ripple of 720 [Hz] which is 12 times the fundamental wave in the output voltage and current. Figure 8 shows the simulation results with a single auxiliary converter applied under the same conditions. It can be seen that the output voltage and current ripples are reduced by turning on the auxiliary converter at about 0.03 seconds. Reactive power is measured at about 80 [MW]. In addition, it was confirmed that the output voltage and current ripples decreased, and in particular, it can be seen that the 720 [Hz] component was greatly reduced.



(a) Input power



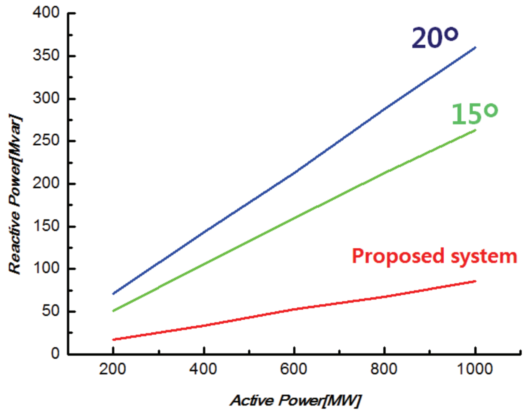
(b) Output voltage



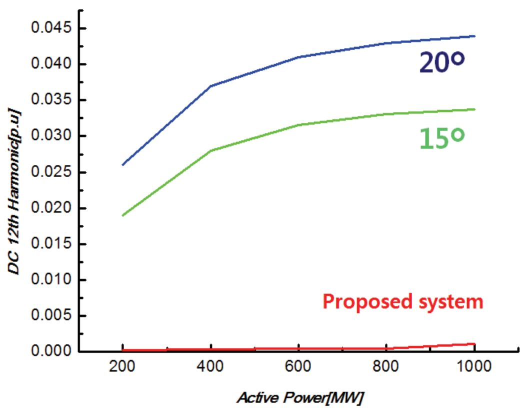
(c) Output currents

Fig. 8 Voltage and currents of proposed LCC-HVDC with a single sub converter. (1000[MW])

Figure 9 shows the input/output characteristics of the conventional and proposed method. As shown in Section 2.1, it can be seen that the slop increases as α



(a) Reactive power vs active power



(b) 12th harmonic of output voltage

Fig. 9 Input/Output characteristics of proposed LCC-HVDC

increases. However, when the auxiliary converter is applied, it can be confirmed that the slop is greatly reduced, and it is confirmed that the reactive power can be reduced by up to 77 [%] under the same active power condition. In Figure 9(b), it can be seen that the 12th harmonic is greatly reduced. and the high-order harmonic increases due to the switching operation of the auxiliary converter. But, it is greatly attenuated by the output filter.

4.2 Experiment result

Figure 10 shows the configuration of the experimental stack for verification of the proposed structure. It consists of a 12-pulse rectifier and its controller, and the proposed auxiliary converter and its controller.

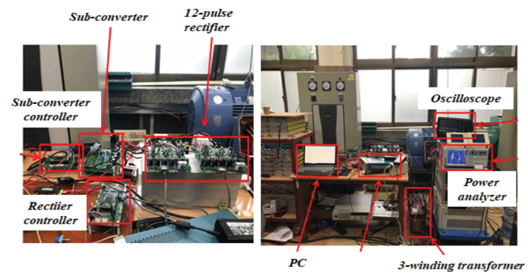
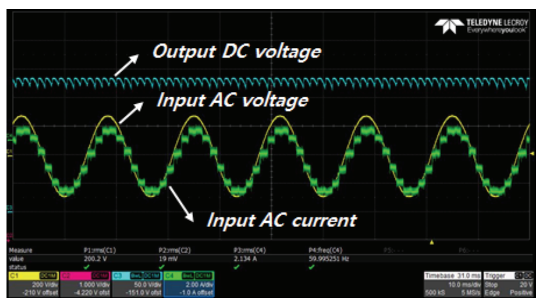
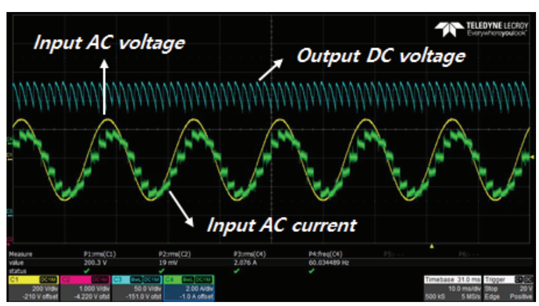


Fig. 10 Experiment stack

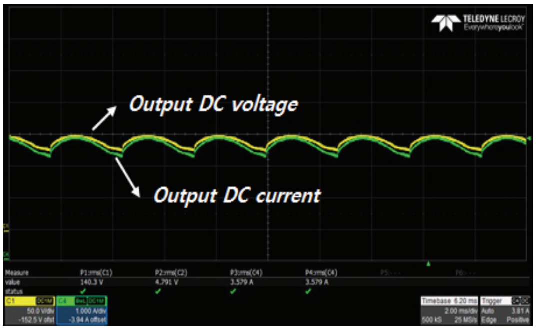


(a) α=5[°]

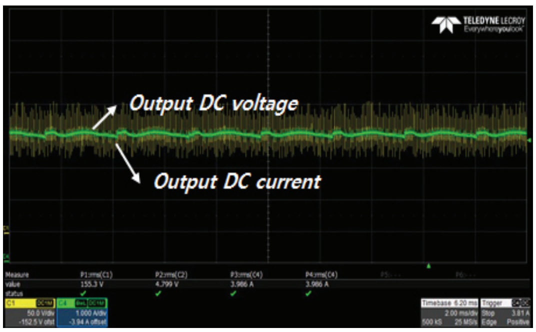


(b) α=20[°]

Fig. 11 Voltages and current according to α.



(a) Conventional output waveforms



(b) Proposed output waveforms

Fig. 12 Output voltage and current.

Figure 11 shows the phase change of the input current according to α of the conventional 12-pulse thyristor rectifier. Figure 11(a) shows the case where α is 5°, and it can be seen that the current phase is close to the voltage in phase. Figure 11(b) shows the case where α is 20°, and it can be seen that the phase difference between voltage and current increases as α increases.

Figure 12 shows the output DC voltage and current of the conventional and the proposed method. In the conventional method, the harmonic of 720 [Hz] appears prominently, but in the proposed method, it can be confirmed that the 720 [Hz] harmonic is greatly reduced by the auxiliary converter.

5. Conclusion

In this paper, to improve the input/output characteristics of LCC-HVDC, a new LCC-HVDC structure combined with a serial auxiliary converter is proposed. By fixing α to a small value, it was possible to increase the reactive power and decrease the amount of change in the reactive power according to the active power. In addition, it was confirmed that the 12th-order harmonics of the fundamental wave, which are structurally generated, can be greatly reduced by controlling the auxiliary converters connected in series. The proposed method can easily improve the performance by adding an auxiliary converter to the already installed LCC-HVDC. Due to the many disadvantages of LCC- HVDC, it is considered that the lifespan of the LCC-HVDC can be further extended through the proposed method in the trend of transitioning to VSC-HVDC.

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