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Design of a laboratory-scale superconducting DC transmission line

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Abstract - The researchers worldwide have been trying to apply high temperature superconducting wire for power system devices. High voltage direct current (HVDC) transmission system has been used for bulk and long-distance power transmission.
The authors designed a laboratory-scale superconducting DC transmission line to investigate its applicability to an HVDC system. The superconducting DC transmission line was simulated in connection to a laboratory-scale HVDC system using PSCAD/EMTDC.
The operating characteristics of the superconducting DC transmission line connected to HVDC system and the effects of the superconducting DC transmission line on HVDC system were analyzed and compared with the results of a conventional DC transmission line. The results of operating characteristics for the superconducting DC transmission line were discussed in detail.

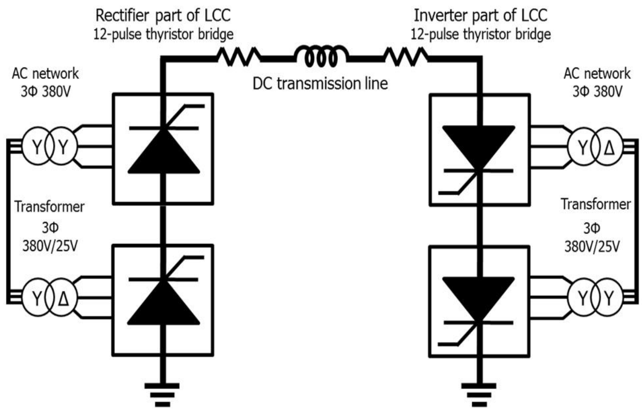
1. Introduction

Many kinds of high temperature superconducting (HTS) devices, such as rotating machine, transformer, fault current limiter, reactor and power cable are being developed in many countries due to several advantages of HTS wire [1]. Transmission of bulk power over long distance based on high voltage direct current (HVDC) is continuously required for effective power transmission from a remote large scale power plant including hydroelectric, thermal, nuclear and renewable power plant [2]. It has been undertaken to apply the HTS devices to the AC power network. Besides, the utility company is researching to apply HTS DC cable to an HVDC system [3]. Before applying the superconducting DC transmission line including an HTS cable and an HTS DC reactor to a real HVDC system, the feasibility study is needed through a simulation.
The authors designed a laboratory-scale superconducting DC transmission line including an HTS DC cable and an HTS DC reactor to examine the operability of the superconducting DC transmission line connected to an HVDC system. A line commutated converter (LCC) type HVDC system which consists of a rectifier, an inverter, four transformers, and a controller, and the superconducting DC transmission line was modeled and simulated in PSCAD/EMTDC program.
In this paper, the operational characteristics of the superconducting DC transmission line in the HVDC system were analyzed and described with results comparison between the conventional DC transmission line and the superconducting transmission line under the same system conditions. Through the results, the operability of the superconducting DC transmission line in the LCC type HVDC system was demonstrated.

2. Design of a superconducting DC transmission line

2.1 The DC converters

A laboratory scale LCC type HVDC transmission system was designed. The HVDC system was composed of thyristor-based converters, wye-wye and wye-delta transformers, DC transmission line and controller as shown in Fig. 1. Each converter including rectifier and inverter of the HVDC system was composed of a twelve-pulse thyristor bridge built with two six-pulse bridges to reduce the harmonics on both sides of converters. The two converter



<Fig. 1> Configuration of the laboratory scale HVDC transmission system

bridges of the rectifier and the inverter were connected in series on the DC side and in parallel on AC side through wye-wye and wye-delta 380/25 V step-down transformers. The DC voltage of the converters is controlled by the firing angle and calculated by (1).

$$V_d = \frac{3\sqrt{2}}{\pi} V_{L-L} \cos\alpha - \frac{3X_c}{\pi} I_d \tag{1}$$

where, V_{L-L} is the phase-to-phase rms commutating voltage in secondary side of the converter transformer, a is the firing-delay angle, X_c is the commutation reactance of the converter transformer, and I_d is the DC current.
Both ends of the HVDC system were connected to a commercial 380 V, 60 Hz AC network. In the case of rectifier, current and voltage controller were used for main and sub controller of the rectifier, respectively. In the case of inverter, voltage and current controller were used for main and sub controller of the inverter, respectively.

2.2 The HTS DC cable

A 20 m HTS DC cable was designed to demonstrate an operability of HTS DC transmission line in connection with the LCC type HVDC system. The inductance of the HTS DC cable was calculated by (2) to simulate the HVDC system including HTS DC transmission line.

$$L = \frac{\pi\mu_0 r^2}{L_p^2} + \frac{\mu_0}{2\pi} ln\frac{D}{r}\ [H/m] \tag{2}$$

where, μ_0 is the space permeability, r is the radius of cable former [m], L_p is the winding pitch of HTS wire [m], D is the geometric mean radius [m].
The minimum bending diameter of the HTS wire was considered to determine the radius of the cable former. The design parameters and the calculation results are described in Table 1.

<Table 1> The design parameters of the HTS DC cable

Contents	Values
Rated current of the cable	100 A
DC critical current of HTS wire	200 A @ 77 K, self-field
Radius of the conducting layer	0.015 m
Winding pitch of HTS wire	0.3 m
Length of the cable	20 m
Inductance of the cable	0.0169 mH

2.3 The HTS DC reactor

A HTS DC reactor was designed for the same purpose with the HTS DC cable. The HTS DC reactor has taken the form of single pancake coil (SPC) using 2G HTS wire. The inductance of the coil was calculated by (3) [4], and confirmed using FEM tool. The design parameters and the calculation results are described in Table 2.

$$L = 0.001 \times n^2 \times a \times P \times f\,[\mu H] \tag{3}$$

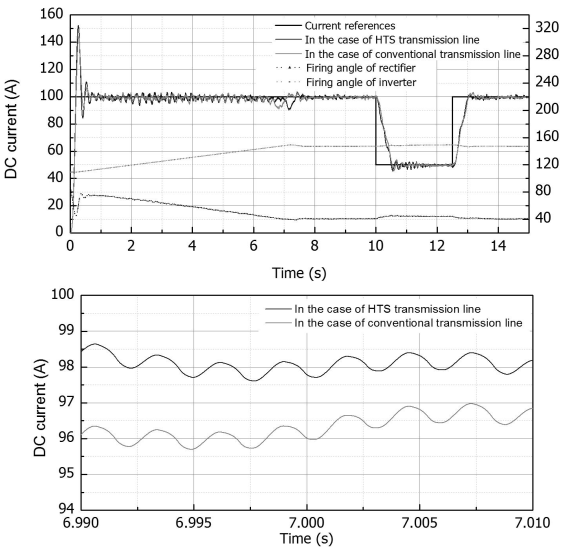
where, n is the number of turns, a is the mean radius of the winding [cm], c is the thickness of the winding [cm], P is the factor for the disk having the same values of c and a, f is a factor less than unity.

<Table 2> The design parameters of the HTS DC reactor

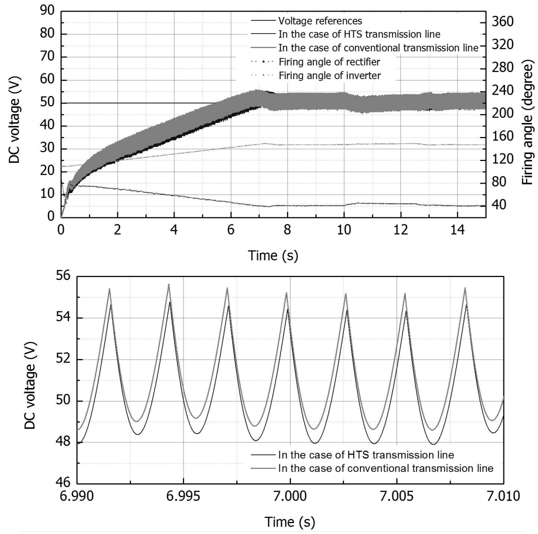
Contents	Values
Inner radius of the coil	12 cm
Mean radius of the winding	13.5 cm
Width/thickness of HTS wire	0.41/0.03 cm
Number of turns	100
Thickness of the winding	3 cm
Disk factor (P)	38.79944
Unity factor (f)	0.95827
Inductance by calculation (by FEM)	5.019 mH (4.987 mH)

3. Simulation and the results

The LCC type HVDC system and the superconducting DC transmission line including the designed HTS DC cable and reactor were modeled in the PSCAD/EMTDC. The integrated HVDC system was simulated with a simple operational scenario which varies from starting to rated DC voltage and DC current conditions, half of the rated DC current condition, and rated DC current condition. The operational characteristics of the HVDC system with the superconducting DC transmission line were analyzed and compared with the results of the conventional DC transmission line under the same system conditions. The parameters of DC transmission lines are described in Table 3.



<Fig. 2> Current characteristics of the HVDC system according to the types of transmission line



<Fig. 3> voltage characteristics of the HVDC system according to the types of transmission line

<Table 3> The parameters of the DC transmission line

Contents	Values
HTS DC cable	0.0169 mH, 0 Ω
HTS DC reactor	5.019 mH, 0 Ω
Conventional DC cable	0.0227 mH, 5.516 mΩ
Conventional DC reactor	5 mH, 12.65 mΩ

Although, in the case of HTS transmission line, the current is larger than that of the conventional transmission line and the voltage is smaller than that of the conventional transmission line, the current characteristics of the HVDC system are almost the same according to the types of transmission line.

4. Conclusions

In this paper, the authors designed a superconducting DC transmission line in connection with a laboratory scale HVDC system. The HVDC system was simulated with a simple scenario, the operational results were analyzed and compared. The current and voltage of the HVDC system are virtually the same characteristics according to the types of transmission line. Through the results, the operability of the superconducting DC transmission line in the LCC type HVDC system was demonstrated.

Acknowledgment

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