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Design and PHILS-based Transient Analysis of a Tri-axial HTS Power Cable

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Abstract

Tri-axial high-temperature superconducting (HTS) power cables are very efficient compared with other HTS power cables due to their reduced use of HTS wires and cryogenic surface area, resulting from the mutually layered structure of the three phases. However, the operating characteristics of tri-axial HTS power cables differ from other cables in a transient-state condition. In order to install HTS power cables in a real grid, feasibility verification through simulation or experimentation is required in advance. Thus, the authors design a tri-axial HTS power cable and implement a power hardware-in-the-loop simulation that consists of a real time digital simulator-based simulation model and hardware devices including a power supply and a 1 m-long tri-axial HTS model cable. Simulation results show the stability verification under steady-state and transient-state conditions.

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Keywords: HTS power cable; PHILS; RTDS; Solenoid type cable; Tri-axial cable.

1. Introduction

High-temperature superconducting (HTS) power cables have advantages, such as the high-current density, the low-loss, and the environmentally friendly characteristics of using liquid nitrogen (LN_2) for cooling and insulation compared to conventional cables. Thus, various designs of HTS power cables have been developed in three single-

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phase, triad-coaxial, and tri-axial HTS power cables in recent years [1-4]. Among them, tri-axial HTS power cables with a mutually layered structure of three phases has several advantages, including a reduced amount of HTS wires and a small cryogenic surface area compared to other HTS power cables. It is expected to effectively solve the problems caused by increases in the electricity demand and limited space. However, the HTS power cables are sensitive to the current density, magnetic fields, and temperature. Also, the operating characteristics in steady-state and transient-state conditions differ from conventional cables. Thus, feasibility verification through simulation or experimentation is required before installing HTS power cables in a real grid [5, 6].

The authors design a 1 m-long tri-axial HTS model cable that has the inductance of a l km-long tri-axial HTS power cable [7]. The 1 m-long tri-axial HTS model cable is fabricated and a power hardware-in-the-loop simulation (PHILS) is implemented for the stability verification and the transient characteristics analysis.

The PHILS consists of a real-time digital simulator (RTDS)-based simulation model and hardware devices, which are a power supply and the 1 m tri-axial HTS length model cable. The simulation model and hardware devices are connected through analog input and output devices. The PHILS scheme, the circuit diagram of the simulation model, and the modeling process of the HTS model cable are discussed in detail. Simulation results show the current distribution under steady-state and transient-state conditions. The results will be used for the stability verification and analysis of the operating characteristics in various types of HTS power cables before applying them to the real grid.

2. Design of a tri-axial HTS model cable

The tri-axial HTS power cable has a three-phase concentric structure that consists of HTS wires wound clockwise and counter-clockwise along the same axis. The spaces between the layers of the cable are filled with cryogenic dielectric material. LN_2, which is a refrigerant used to reach a superconducting state, is injected into the inner core pipe and then exits through the outer cryostat. The structure of the tri-axial HTS power cable is described in Fig. 1 (a) and detailed design parameters are indicated in Table 1 [8, 9]. Using these parameters, a 1 m tri-axial HTS model cable with an inductance of a l km-long tri-axial HTS power cable is designed and the parameters are indicated in Table 2. Inductance is calculated using Eq. (1) [10]. Fig. 1 (b) shows the fabricated 1 m tri-axial HTS model cable. Table 3 indicates the inductance of the tri-axial HTS model cable.

$$L = \frac{\mu N^2 A}{l} \tag{1}$$

where μ is the magnetic permeability, N is the number of turns, A is the area of the core, and l is the length of the cable.

Table 1. Parameters of the tri-axial HTS power cable.

Parameters	Value	Parameters	Value
Voltage / Capacity	22.9 kV/50 MVA	Radius of each phase	17.5 / 21.5 / 25.5 mm
Rated current	1,260 A_{rms}	Radius of the shield	29.5 mm
Type of HTS wires	2G YBCO (width: 4mm)	Winding pitch	+405 / -545 / +795 mm
Insulation thickness	4 mm (using PPLP)	Length of the cable	1 km

a b

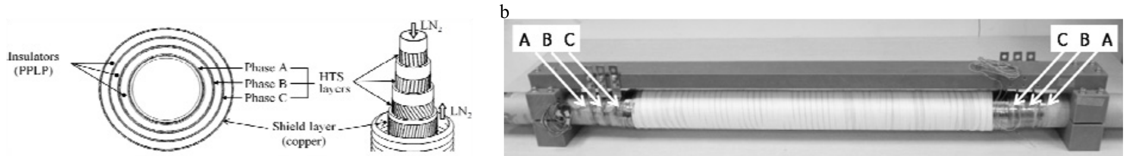

Fig. 1. (a) The structure of the tri-axial HTS power cable; (b) fabricated 1 m tri-axial HTS model cable.

Table 2. Parameters of the 1 m tri-axial HTS model cable as same inductance as 1 km length.

Layers	Radius (m)	Twist pitch (m)	Turns (turn)	Layer length (m)	Wire length (m)	Critical current (A)
Phase A	0.04	0.0054	185	1	46.5	126
Phase B	0.042	0.00592	158	0.94	41.9	116
Phase C	0.044	0.0066	133	0.88	38.4	110
Shield	0.046	0.00721	113	0.82	35.2	

Table 3. Inductance of the 1 m tri-axial HTS model cable.

Layers	Design		Measurement	
	Self (mH)	Mutual (mH)	Self (mH)	Mutual (mH)
Phase A	0.218	M_{ab} 0.163	0.206	M_{ab} 0.173
Phase B	0.172	M_{bc} 0.130	0.177	M_{bc} 0.146
Phase C	0.138	M_{ac} 0.138	0.142	M_{ac} 0.142

3. PHILS-based transient analysis

3.1. PHILS configuration

The configuration of the PHILS is illustrated in Fig. 2. The PHILS is composed of a power system with the tri-axial HTS power cable model in RTDS and hardware devices including the power supply, load, circuit breaker, transformer, and the 1 m tri-axial HTS model cable. The power system in RTDS is a 22.9 kV/50 MVA distribution system and the tri-axial HTS power cable model consists of self and mutual inductance, capacitance, and variable resistance. The mutual inductances between the conductor layer and shield as well as between phases AB, AC, and BC are also considered. The variable resistance receives input data that are calculated using the measured voltage and current from the tri-axial HTS model cable. Table 4 indicates specifications of RTDS simulation model and hardware systems.

Table 4. Specifications of RTDS simulation model and hardware systems.

Contents	Simulation value	Hardware value
Rated voltage	13.2 kV	4.97 V
Rated capacity	50 MVA	500 VA
Rated current	1.26 kA_{rms}	33.1 A_{rms}
Fault current	2.52 kA_{rms}	66.4 A_{rms}
Duration of fault	5 cycle	5 cycle

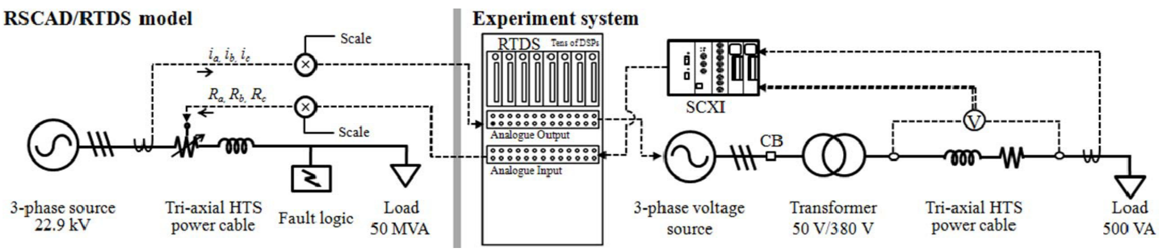

Fig. 2. The configuration of the PHILS.

3.2. Simulation and the results

The PHILS was implemented on a single-line-to-ground fault. In the RTDS simulation model, the rated current is 1.26 kA_{rms}, and the critical currents of each phase are 3.2 kA, 3.7 kA, and 4.2 kA under 77 K, respectively. The fault was initiated at 0.04 s and lasted for 0.083 s. Fig. 3 (a) shows the fault current in RTDS, and this current is transformed to the control signal of the power supply. According to the signal, the voltage was applied to the 1 m tri-axial HTS model cable. The rated current of the 1 m tri-axial HTS model cable is 33.15 A_{rms}. Fig. 3 (b) depicts the cable's fault current. Also, we measured the voltage at both ends of the cable. As a result, the resistance was calculated and quench did not occur.

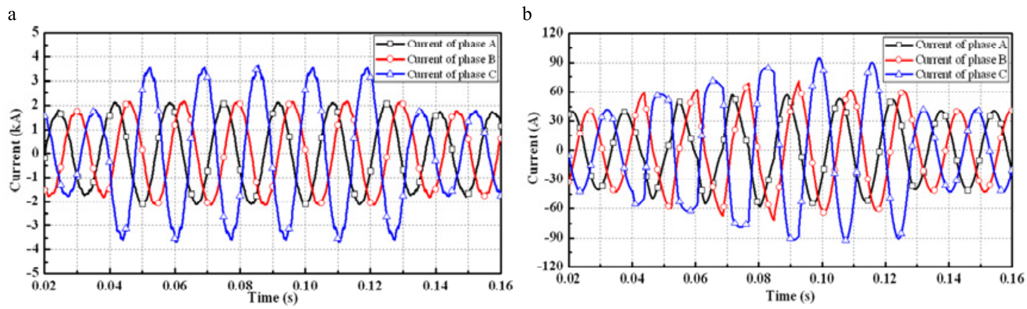

Fig. 3. (a) Fault current in RTDS; (b) fault current in the 1 m tri-axial HTS model cable;

4. Conclusions

In this paper, a 1 m tri-axial HTS power cable that has the inductance of a 1 km tri-axial HTS power cable was designed, and the power hardware-in-the-loop simulation system was configured in order to verify the feasibility of its practical application. The RTDS-based simulation model is a 22.9 kV/50 MVA class power system in which 1 km tri-axial HTS power cable is included. The cable characteristics are realized by the 1 m tri-axial HTS model cable. The PHILS was implemented on a single line to ground fault. Simulation results show both conditions of the power system and the model cable. Using this method, the stability of the tri-axial HTS power cable has been verified under the transient condition. In the future, the results will be used to apply the tri-axial HTS power cable to the grid with additional results on various transient conditions using PHILS.

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