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The Study of Applied HTS DC Cable on VSC Based Power Transmission System

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Abstract

This paper describes the operation characteristics of using superconducting cables in dc transmission systems, focusing on dc current and cable parameters. A superconducting power transmission system need not operate at high voltage levels to reduce I^2R losses. This eliminates the need for high voltage insulation and large transformers. Voltage source converter (VSC) transmission has come into use in the last decade. The VSC transmission is often used in cases where an ac system is not practical, generally due to long underground or undersea cables, and excessive losses. The combination of VSC and low-voltage dc (LVDC) superconducting transmission cables could be a good solution to minimize the losses. Issues related to the impact of superconducting cables on VSC LVDC transmission system will be presented along with computer simulation results.

Keywords: *High temperature superconductor, low-voltage dc transmission, superconducting cable, voltage source converter.*

1. Introduction

Recently, superconducting power cables using high temperature superconductor (HTS) are under development in many institutes. In such a trend, it is expected to apply them to power transmission and distribution systems. A typical application, low voltage power transmission could be a significant role of power grids in the future. A superconductor power system would operate at low voltage, resulting in a single voltage level from generation to distribution subsystem. Superconductor has extremely low impedance, result in significantly reducing I^2R losses from the lines. Low voltage transmission reduces the need to operate transmission systems at EHV levels for long distance transmission. Low voltage operation requires neither high voltage insulation nor large transformers [1]-[5].

The uses of ac transmission with HTSs have some problems. The materials have major problems related to 60-cycle fields. The periodic field reversal generates hysteric losses in the superconductor, and eddy current losses in any copper or aluminum materials which surround the superconductors [6].

The HTS dc cables represent a very attractive alternative to HTS ac cables. The conductor loss in HTS dc cables could be negligible. There is no reactive power and no loss in the insulation. Also, the HTS dc cables could be very compact. These make the design of HTS dc cables much less complex than ac case [7].

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The reduced loss with HTS dc cables creates new problems, since superconductor has chances to lose its characteristics and having resistance value. In this case, the quench conductor carries the current momentarily during superconductor move into its superconducting state. It takes long time to recover superconducting state when large current flow through HTS [8]. To solve the problem, one solution is to use circuit breaker to prevent current flow through HTS. The case study is carried out to verify that the correlation of the circuit breaker operation and HTS cable characteristics.

2. System Design

2.1. Merits of Superconducting DC Transmission System

As well known, superconductor has some loss in ac operation. Besides, insulating material generate considerable dielectric loss under the ac electrical field. Therefore, to minimize the losses, dc system is much better than ac one. Superconducting dc cable can take maximum advantage of the characteristics of superconductivity. The advantages are as follows [6], [9].

1) The peak of rated current is smaller than ac one by in dc transmission system. The superconducting dc power cable can transfer larger power than ac one below its critical current.
2) There is no current imbalance between HTS tapes caused by the imbalance of inductances.
3) There is no eddy current loss in the conductor or in structural members.
4) There is no dielectric loss in electrical insulation materials and a smaller dielectric stress allows for reduced thickness.
5) There is no mechanical oscillation or noise induced by pulsated electromagnetic force.
6) The dc transmission line does not generate any reactive power.

These properties open the possibility to transfer energy with low voltage and high current.

2.2. Superconducting DC Cable

The superconducting dc cable design selected for this paper is shown in Figure 1. The dimensions of each component of the cable are given in follows [8], [10].

1) The mandrel bore is a support tube for the conductor components. Unlike a conventional copper wire conductor, a superconducting wire (a flat tape) has a limiting, minimum bending radius based on a maximum permissible bending strain.
2) The quench conductor is made of copper wires that form one or more concentric layers. The role of the conductor is to carry the current momentarily should the overlaying superconductor be driven out of its superconducting state (such as during a fault).
3) The superconductor operates at normal condition. The current carrying capacity of each tape is determined by its critical current at the operating magnetic field and temperature and a suitable margin.
4) The conductor shields provide controlled interfaces between superconductor and the insulation.
5) During normal operation, the superconductor will be at ground potential. The insulation prevents arcing between superconductor and outer sheath which always remains at ground.
6) The sheath of stainless steel contains the entire cable core structure.

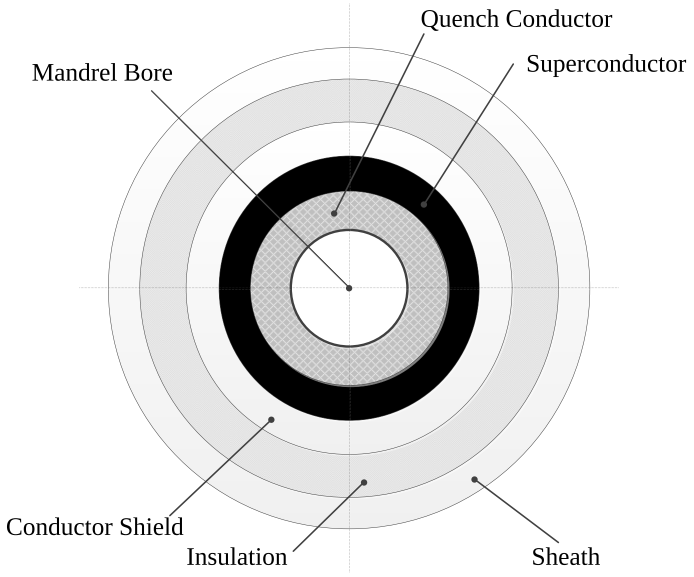

Figure 1. Cross-section of Superconducting DC Cable

It is hoped that this structure can be utilized as an emergency case when there is a problem with superconductor.

2.3. Low-voltage DC Transmission

Over the last years, voltage source converter (VSC) with pulse-width modulation (PWM) based high voltage direct current (HVDC) transmission has started to come into use. This system is based on a modular design, reducing the installation time and the footprint [5]. The PWM techniques has to be controlled the active power delivered to the ac system and, at the same time, to control the reactive power as required for proper operation of the ac system. The power can be controlled by the phase angle of the converter reference signal, whereas the reactive power can be controlled by changing the magnitude of the reference signal of the converter in Figure 2. It means that the real power transfer can be changed rapidly without altering the reactive power exchange with the ac network or waiting for switching of shunt compensation [11].

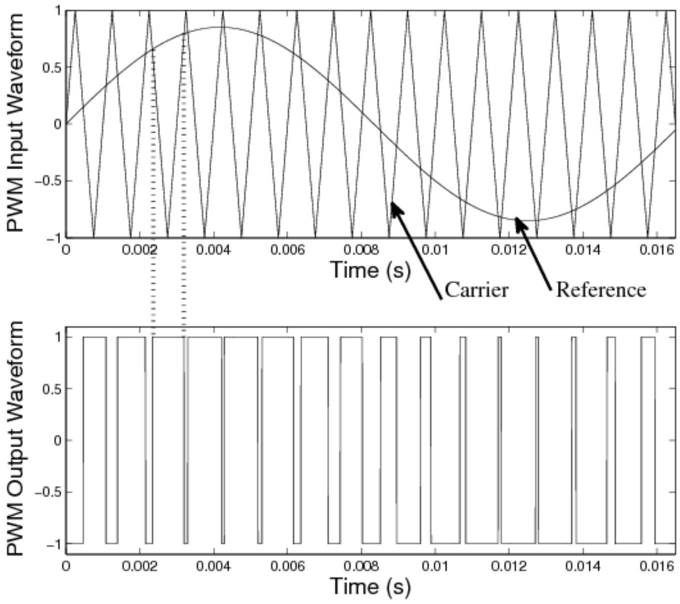

Figure 2. Output Voltage from a Single-phase, Two-level PWM Converter

The converters in VSC transmission are able to supply power to weak or passive ac load systems. The VSC transmission is often used in case where an ac system is not practical, generally due to long underground or undersea cables, and excessive loss. One common application is supplying power to isolated island systems without adequate local generation to provide reactive support for conventional HVDC converters. However, the high voltage VSC technology has two major drawbacks [12].

1) The overall losses are high due to high switch frequencies and high switch losses with many switching elements.
2) Complexity and cost are increased due to stacking of switching element. For a 100 kV stack approximately 200 elements are needed.

By using low voltage, it is possible to reduce the need for stacking of switch elements. It means that the VSC system with superconducting transmission cables which is called low-voltage direct current (LVDC) transmission system reduce losses caused by switching elements. Also, there is no conductor loss in steady-state operation because the resistance of a superconducting dc cable is zero. However, the reduced losses with superconducting cables create new problems since decreasing losses also decreases the damping normally provided by resistive elements in dc system [13, 14].

Converter control action can be used to solve low damping problem in steady state operation [5]. However, when superconductor line has loss of its characteristics, there is a slow thermodynamic recovery problem of the superconductor line, since the dc current still flow the line. It means that all the current does not bypass to quench conductor line. It is hard to handle the problem by using converter control action. To avoid the problem, the circuit breakers of superconductor line have to operate bypassing the current to quench conductor line. The circuit breakers operate when the current flow in circuit breaker is lower than its current chopping limit. The current level depends on resistance value of superconductor line when it has loss of its characteristics.

3. Sample System

3.1. System Configuration

A sample system is presented in Figure 3 to illustrate operating characteristics of the proposed LVDC transmission system.

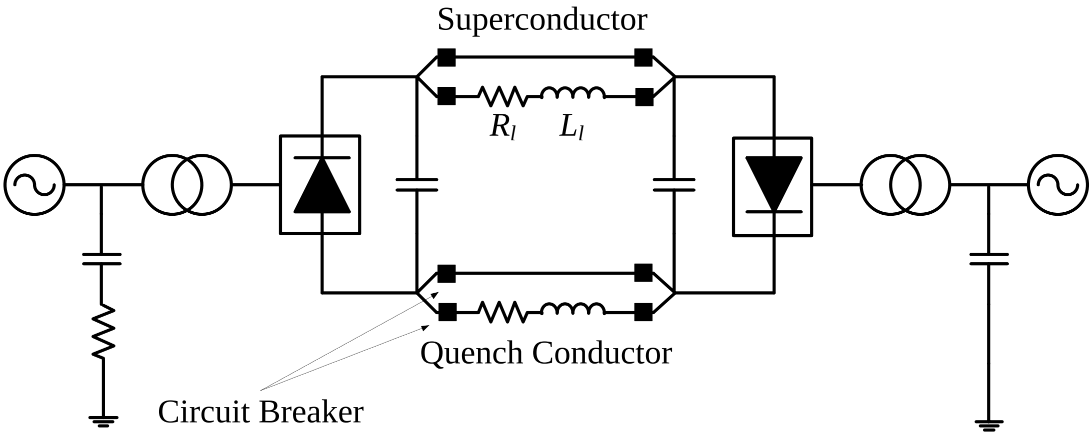

Figure 3. LVDC Transmission System with VSCs.

The capacitor banks at both the ends of the superconducting cable form the stiff voltage source necessary for appropriate operation of the VSCs, which are capable of operation as either an inverter or a rectifier. These VSCs provide for bi-directional power flow capabilities. An LC filter and transformer are used to interface the VSCs to the ac system for voltage matching. The superconducting cable system is located between rectifier and inverter.

The system properties of the superconducting cable used in the sample system are: length: 100 km; rated power: 75 MW; rated dc voltage: 110 kV; rated dc current: 6.8 kA; quench conductor inductance: 11.936 mH/km; quench conductor resistance: 50 mΩ/km.

3.2. Superconducting Cable System

The superconducting dc cable system consists of return and transmission cables. The cables include superconductor line and quench conductor line which is made of normal conducting materials. The quench conductor line has impedance value. Each line has two circuit breakers at both ends. Compared to conventional HVDC cables, the superconducting dc cable operates at a relatively low voltage and high current. The ground return would be a significant fraction of the total voltage within the system. As a result, it is impractical to allow a ground current in a superconducting dc system. If there is a mismatch of transmission and return current, a net magnetic field will arise around each of the cables [8].

Each of superconductor and quench conductor lines has two circuit breakers which is components in the power system that can open the circuit during a contingency. The circuit breakers create an arc by open contacts. Then the dielectric strength across the arc has to be increased so the arc extinguishes when the current becomes zero, which it becomes every half cycle in an ac system [15]. However, dc has no natural current zero. One possibility to interrupt dc is to use a breaker together with a resonant circuit. The resonant circuit creates a voltage zero, and if the breaker then opens at zero voltage no arc will be generated [16]. The other possibility to interrupt dc is to use superconductor characteristics in LVDC system. When quenching is applied to superconductor cable, superconductor could have resistance value and it prevent to current flow through superconductor line.

4. Simulation Results

In order to evaluate the integration behavior of the superconductor dc cable with the LVDC, the power systems computer aided design /electromagnetic transients including DC (PSCAD /EMTDC®) software is used. With this digital program, complex networks and control systems of arbitrary structure can be simulated. A quenching is applied at the cable in order to analyze the current characteristics which depend on resistance value of superconducting cable.

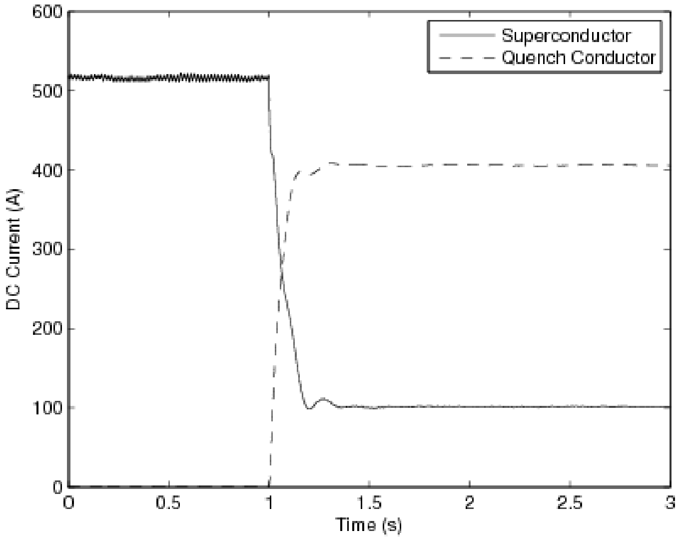

Figure 4. Computer Simulation Response of the DC Current with Different Lines

Figure 4 shows the dc current values of superconductor and quench conductor when quenching is applied at 1 s. All the current flows through superconductor line because quench conductor has 5 Ω and 1.936 H but superconductor has zero impedance before quenching. The dc current flows through both quench conductor and superconductor line after quenching. It makes slow thermodynamic recovery problem since the 100A dc current still flow the superconductor line which has 20 Ω. However, the minimum value of dc current decreases with increasing the resistance of the quenched superconductor.

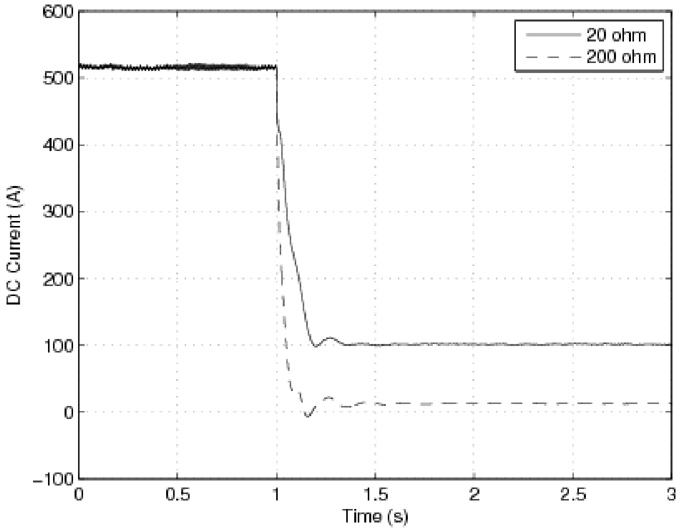

Figure 5. Computer Simulation Response of the DC Current with Different Resistance Values of Quenched Superconductor Line

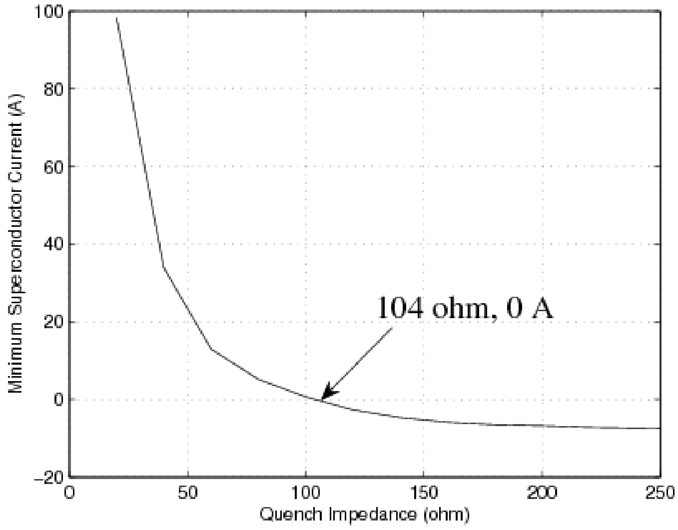

Figure 6. Minimum Superconductor Current Values with Various Quenching Resistance of Superconductor

Figure 5 shows the waveform of the superconductor line current with different resistance when quenching is applied at 1 s. The current value with 200 Ω of quenching resistance is lower than the value with 20 Ω of that after quenching. Although the current is lower in case with large resistance value, there is still thermodynamic recovery problem because the current flow in the superconductor line is not completely zero. To solve this problem, the circuit breakers have to operate to prevent the current flow through the superconductor line. The circuit breakers operate under its current chopping limit which is supposed to be zero in this simulation.

Figure 6 shows the minimum superconductor current values with various quenching resistances of superconductor line when quenching is applied. The minimum current value decreases with increasing quenching resistance. The current value is zero when the resistance is 104 Ω. It means that the circuit breakers operate when superconductor has greater than 104 Ω of quenching resistance in this simulation case.

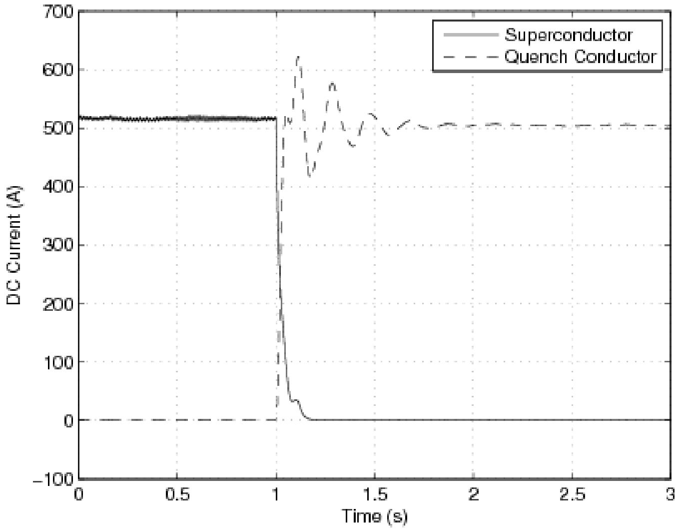

Figure 7. Computer Simulation Response of the DC Current with Different Lines when Circuit Breakers Operate

Figure 7 shows the dc current values of superconductor and quench conductor when quenching is applied at 1 s and circuit breakers operate at 1.2 s. The superconductor line has 110 Ω of quenching resistance in this case. All the current flows through superconductor line before quenching like in Figure 4 case. However, all the current flows through quench conductor line after circuit breakers operation.

5. Conclusions

This paper analyzes the effect of a superconducting dc cable on the VSC LVDC system in determining the size of the quenching resistance of the cable. The superconducting dc cable has zero impedance at steady state operation. However, the HTS has resistance value when it loses its characteristics. The resistance value affects on circuit breakers operation which prevents the dc current flow through superconductor when quenching occurs.

The simulation results showed that the larger quenching resistance value of superconductor could be good solution of thermodynamic recovery problem. This study also showed the minimum quenching resistance value of superconductor to operating circuit breaker.

In practice, this study could be used as a decision-making guide for setting up a HTS dc cable to VSC LVDC system.

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