Analysis of DC Power Transmission Using High $T_c$ Superconducting Cables

Jun-Lian Zhang and Jian-Xun Jin

Abstract—A conceptual superconducting DC cable model is designed and its magnetic fields distribution is analyzed with Ansoft/Maxwell soft. A DC Power transmission system is also studied by using the Matlab/Simulink. With the DC Line and AC Ground Fault, the system losses analysis is introduced. The analysis results mainly include the magnetic fields distribution of the HTS cable model with Ansoft/Maxwell, the system loss, the DC Line and AC Ground Fault with Matlab/Simulation.

Index Terms—Ansoft/Maxwell, DC transmission system, HTS cable, power transmission loss.

1. Introduction

The 21 century is the age of superconducting cable, some of the traditional grounding cables could be substituted with high temperature superconducting (HTS) cables before 2020. The resistive energy losses consumed on power transmission lines become enormous as the high capacity delivery power required by our dramatically developed society. Using HTS technology is an alternative way to resolve the principal technical difficulties to achieve high efficient power transmissions. The HTS cable will especially benefit to DC power transmission due to zero resistive loss and lowering voltage levels. The DC networks can operate with low voltage and high current allowing direct connection of the generators to the rectifiers, eliminating the need for high voltage insulation and transformers$^{[1]-[3]}$.

In this paper, HTS cables and their application to develop a DC power transmission system with the advantages of large transport current capability, no resistive loss and compact systems will be studied and identified. Technical assessments of DC electrical power transmission system behaviors with the use of HTS DC cable technology will be carried out with the HTS DC cable and the system model be built.

2. Magnetic Analysis

Generally, a HTS cable of parallel configuration is used in superconducting electric power field and the current flowing in the HTS tape is unchangeable when the cable is operated under DC condition, therefore, there is only steady magnetic field existing between the HTS tapes. The magnetic field distribution in the HTS cable can be calculated by using finite-element method (FEM). Ansoft/Maxwell soft is chosen to simulate the magnetic field distributions in and around the cold dielectric (CD) and warm dielectric (WD) HTS cables, where the HTS materials are assumed to be linear ones. The total current of the conductor layer is assumed to be 1 kA, and the relative permeability is assumed to be 1.

2.1 A Conceptual Cold Dielectric Cable Model

The cold dielectric (CD) HTS DC cable has a concentric structure. The main body of this cable from inner to outer is former, compounded conductor, dielectric and compounded shield. Copper composed with parallel placed HTS tapes are used as compounded conductor and compound shield. The whole cable core is covered by a thermally insulated double wall cryostat. The LN$_2$ goes through the hollow former and return at the other end in the space between the outer layers of HTS tapes and below the cryostat. The main parameters of the CD cable are shown in Table 1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Outer Radius (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LN$_2$</td>
<td>8</td>
</tr>
<tr>
<td>Former</td>
<td>9</td>
</tr>
<tr>
<td>Insulator1</td>
<td>9.4</td>
</tr>
<tr>
<td>Cu1</td>
<td>10.5</td>
</tr>
<tr>
<td>Conductor(YBCO HTS tape)</td>
<td>10.8</td>
</tr>
<tr>
<td>Cu2</td>
<td>11</td>
</tr>
<tr>
<td>Insulator2</td>
<td>12</td>
</tr>
<tr>
<td>Cu3</td>
<td>13</td>
</tr>
<tr>
<td>Shield(YBCO HTS tape)</td>
<td>13.3</td>
</tr>
<tr>
<td>Cu4</td>
<td>13.5</td>
</tr>
</tbody>
</table>

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Fig. 1 illustrates the simulated results of magnetic field distributions of the CD cable model in Ansoft/Maxwell, where (a) is magnetic field distributions near the tapes, and (b) is magnetic field distributions of the cable along the radius from 0 mm to 15 mm.

The main magnetic field is distributed between the HTS conductor layer and shield layer, and almost zero field at the outer areas of the cable exists because of the CD configuration. The shield current is the same magnitude but opposite direction comparing with the HTS conductor current, and it serves as a shielding facility to the magnetic field caused by HTS conductor current. The total field applied on the HTS tape includes the self-field and the field produced by other HTS tapes in the cable, which should be less than 0.03 T for practical application.

2.2 A Conceptual Warm Dielectric Cable Model

The warm dielectric (WD) HTS DC cable design also has a concentric structure. The main body of the WD HTS DC cable from inner to outer is former, compounded conductor that is copper composite with parallel placed HTS tapes, and a thermally insulated double wall cryostat. The whole cable core is covered by ordinary dielectric materials. The LN$_2$ goes through the hollow former and returns at other channels. The main parameters of the WD cable are shown in Table 2.

Table 2: Size of WD cable model

<table>
<thead>
<tr>
<th>Materials</th>
<th>Outer Radius (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LN$_2$</td>
<td>8</td>
</tr>
<tr>
<td>Former</td>
<td>9</td>
</tr>
<tr>
<td>Insulator1</td>
<td>9.4</td>
</tr>
<tr>
<td>Cu1</td>
<td>10.5</td>
</tr>
<tr>
<td>Conductor(YBCO HTS tape)</td>
<td>10.8</td>
</tr>
<tr>
<td>Cu2</td>
<td>11</td>
</tr>
<tr>
<td>Heat insulator</td>
<td>12</td>
</tr>
</tbody>
</table>

Unlike CD cable, a strong magnetic field is distributed around the WD cable because of lacking shield layer. So it may lead disturbance to the nearby communication lines or HTS cables and decrease the capacity of the cable.

Fig. 2 illustrates the simulated results of magnetic field distributions of the WD cable model in Ansoft/Maxwell, where Fig. 2 (a) is magnetic field distributions of the whole cable, and Fig. 2 (b) is magnetic field distributions along the radius from 0 mm to 15 mm.
Assume that the total current is 1 kA in HTS conductor layer and the current density is 50 A/mm$^2$, and the filling coefficient is 100%. Fig. 1 and Fig. 2 illustrate the magnitude of magnetic field distributions of CD and WD HTS cable, respectively. The magnetic performance of CD cable is better than that of the WD cable. The HTS conductor is assumed to be ordinary linear conductor during the simulation, so the magnetic field exists in the HTS conductor.

Fig. 3 illustrates the variation of critical current ($I_c$) about the unit YBCO HTS conductor (4.0 mm×0.2 mm) with magnetic field in applied different directions, which shown that the anisotropism of the Yttrium based oxides are relatively infirmness at LN$_2$ temperature. However, its magnetic field tolerance shows that the cable model design is reasonable.

2.3 Parameters Calculation

The inductance and capacitance of the coaxial cable can be calculated from the basic equations of electromagnetism. The inductance is proportional to the integrated magnetic field energy stored around the conductor. In the case of a coaxial HTS cable, the magnetic field is contained entirely in the narrow cylindrical space between an inner HTS conductor (at a radius from $R_1$ to $R_2$) and the HTS shield conductor (at radius $R_s$). This assumes that the shield conductor is grounded, and it is designed to carry a reverse current which can fully compensate the current in the inner conductor, with negligible flux leakage through shield$^4$.

$$L = \frac{\mu_0}{4\pi} \tan(\theta) + \frac{\mu_0}{2\pi} \ln \left( \frac{R_s}{R_1} \right) + \frac{\mu_0}{2\pi} \ln \left( \frac{R_1}{R_2} \right)$$

$$\times \left[ \frac{R_1^4 - R_s^4}{4} + R_1^4 \ln \left( \frac{R_s}{R_1} \right) - R_2^4 \ln \left( \frac{R_2}{R_s} \right) \right]$$  

(1)

where $R_1$ is inside radius of the inner conductor, $R_2$ is outside radius of the inner conductor, $R_s$ is shield radius, $\theta$ is pitch angle of inner conductor helical winding, and $\mu_0$ is permeability of free space.

The cable capacitance $C$ per length (in units of F/m) is calculated using the following equation$^4$:

$$C = \varepsilon_0 2\pi \varepsilon_r / \ln \left( \frac{R_s}{R_1} \right)$$  

(2)

where $R_s$ is radius of shield (m), $R_1$ is outside radius of conductor (m), $\varepsilon_0$ is permittivity of free space, and $\varepsilon_r$ is dielectric constant.

3. Simulation and Analysis

Matlab/Simulink is a software package for modeling, simulating, and analyzing dynamic systems. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two. Systems can also have different parts that are sampled or updated at different rates. Here Matlab/Simulink is used to simulate a DC transmission system based on HTS transmission line.

3.1 A DC Power Transmission System

Most DC transmission systems adopt 12-pulse current converters using two 6-pulse thyristor bridges connected in series. Fig. 4 illustrates a DC power transmission system prototype in Matlab. A 1000 MW (500 kV, 2 kA) DC interconnection is used to transmit power from a 5000 MVA (500 kV, 60 Hz) system to a 10000 MVA (345 kV, 50 Hz) system in Matlab/Simulink$^5$. The AC systems are represented by damped L-R equivalents. The system is programmed to start and reach a steady state. Practically, the reference current is applied first and then the reference voltage is applied to observe the dynamic response of the system. Finally, a stop-signal sequence is initiated to make the power transmission smoothly down before blocking the converters.

In this section, the 0.015 $\Omega$/km and 0.00015 $\Omega$/km DC line represent the common DC cable and HTS DC cable, respectively. A set of AC filters are used to reduce the odd multiple harmonic current and placed on each side of the AC system. A smoothing reactor is adopted on each side of the DC line.

3.2 Power Losses Simulation

The power can be obtained by measuring the active power between the sending terminal and receiving terminal. Rated voltage and current are taken in the all analysis and calculation. The sending power subtracts the receiving power is the power losses including all the losses consumed by transformers, filters, converters and transmission line, i.e., the total power losses of the whole power transmission system.
Fig. 4. A DC power transmission system.

Fig. 5 shows the sending power of the DC transmission system, and the power losses with different line resistance and different voltage level of the DC transmission system, where \( P_1, P_2, P_3, P_4 \) are the power loss when a 400 kV, 2.5 kA, 0.015 \( \Omega \)/km DC line, a 500 kV, 2 kA, 0.015 \( \Omega \)/km DC line, a 400 kV, 2.5 kA, 0.00015 \( \Omega \)/km DC line and a 500 kV, 2 kA, 0.00015 \( \Omega \)/km DC line is used respectively. The left segments of the curves in Fig. 5 correspond to the ramped start-up, and some pulses on the condition of zoom in statement are generated because of the harmonious current and voltage on the DC line.

The simulation results show that the power losses of the system increase owing to the increase of resistance on transmission line and the decrease of transmission voltage level. If superconducting technology is applied to the DC transmission system, even if a lower voltage level (400 kV) shown as \( p_1 \) is adopted, the power losses are lower than that of the common DC transmission system operated at a higher voltage level (500 kV) shown as \( p_4 \). The harmonics are generated because of lacking damp by decreasing line resistance shown as \( p_4 \).

3.3 DC Line and AC Ground Fault

In this section, some simulated parameters are changed in Matlab/Simulink\(^5\) to deactivate the steps applied on the reference current in the Master Control and in the Inverter Control blocks, a DC fault is applied at \( t=0.7 \) s and ends at \( t=0.8 \) s.

The DC voltage and current on the side of rectifier and inverter under different line resistance are shown in Fig. 6, where \( V_1 \) and \( I_1 \) are the DC voltage and current when a 0.015 \( \Omega \)/km DC line is used; \( V_2 \) and \( I_2 \) are the DC voltage and current when a 0.00015 \( \Omega \)/km DC line is used; Fig. 6 (a) is DC voltage and current on the side of rectifier; Fig. 6 (b) is DC voltage and current on the side of inverter. The DC current increases to about 2.2 p.u because of the discharging of capacitance on the DC line, the rectifier firing angle is forced to protect the DC line when detecting a low DC voltage on the side of rectifier. The rectifier operates in inverter mode and the DC line voltage becomes negative. The energy stored in the DC line returns to the AC system and then the fault current will be rapidly reduced. When \( t=1.1 \) s, the DC line current decreases to 1.0 p.u. Some voltage and current oscillations are occurred at...
the side of inverter during the fault time. When reducing
the line resistance, the same waveform of DC voltage and
current are shown as \( V_2 \) and \( I_2 \) in Fig. 6.

![Fig. 6. DC voltage and current on the side of rectifier and inverter at AC line fault: (a) rectifier and (b) inverter.](image)

![Fig. 7. DC voltage and current on the side of rectifier at AC grounding fault.](image)

Reset the simulated parameters, an AC line-to-ground fault is applied at \( t=0.7 \) s at the Inverter Control blocks, the DC wave-forms are shown in Fig. 7, where \( V_1 \) and \( I_1 \) are DC voltage and current when a 0.015\( \Omega \)/km DC line is used, \( V_2 \) and \( I_2 \) are DC voltage and current when a 0.00015\( \Omega \)/km DC line is used. When the ground fault is applied, the current increases to 2 p.u, shown as \( I_1 \) and \( I_2 \), and the voltage decreases to negative value, shown as \( V_1 \) and \( V_2 \) quickly. During the AC grounding fault, the fault current drops to a small value, following with oscillations till the fault ends at \( t=0.8 \) s and the system recover to steady state approximately at \( t=1.1 \) s. So the decrease of line resistance does not influence the restoration of AC grounding fault.

The demo of “Thyristor-Based HVDC Link” in Matlab/Simulink is used to analyze the power losses and some dynamic performances including the DC fault, AC fault and the faults restoration. Based on the simulation results, conclusions can be made that HTS technology can be taken into HVDC system with some more essential benefits but no additional disadvantage.

### 4. Loss Analysis of the Transmission System

A HTS DC transmission system mainly has three components, i.e. converter station, HTS cable system and grounding system. Therefore, the total losses include the converter station loss on each side of the HTS cable system, the loss of the HTS cable system and grounding system.

The main equipments of a converter station include conversion transformers, smoothing reactors, AC/DC filters, and reactive power compensators. The loss mechanism of these equipment are different from each other, harmonics are generated both on the AC sides and DC sides, which may cause some additive losses through conversion transformers, smoothing reactors and AC/DC filters. A few charge points between zero charge and full charge are chosen to calculate the losses including the converter station loss, mainly divided into heat standby loss (no-load loss and steady loss) and operating loss (heat standby loss and load loss). The losses of converter station can be obtained by calculating the loss of each component in the converter station. Table 3 summarizes the percentages of different loss items of converter station\(^6\), it shows that the loss form conversion transformers and thyristors take up the principal loss of the converter station. So reducing the loss consumed by converter transformers and thyristors is important to decrease the total converter station loss.

<table>
<thead>
<tr>
<th>Items</th>
<th>Loss percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Converter transformers</td>
<td>~50%</td>
</tr>
<tr>
<td>Thyristor valves</td>
<td>~35%</td>
</tr>
<tr>
<td>Smoothing reactors</td>
<td>~5%</td>
</tr>
<tr>
<td>AC filters</td>
<td>~5%</td>
</tr>
<tr>
<td>Other Losses</td>
<td>~5%</td>
</tr>
</tbody>
</table>

A HTS cable is proposed to be applied as transmission conductor in HVDC transmission system, with an aim to reduce the power loss. The power loss in a DC HTS cable is negligible when operating below its critical current. The only energy loss is keeping the low temperature required by the HTS cable system. The loss of the transmission line is described by the percentages of the total transmitted power. There are three principal contributions: HTS material, insulation, and cryostat to the total loss and reactive power of HTS cables\(^7\). HTS DC cable has no reactive power and virtually no loss in the insulation, leaving only the heat leak as a loss source. The design and optimization of DC HTS cables will be easier comparing...
with that in the AC case.

The grounding system is one of the critical parts of HVDC transmission system, which contains grounding line loss and grounding pole loss. The voltage of the grounding line is very low on the normal condition and it needs not take the loss into account. The only loss is caused by the current flowing into the resistance. Therefore, the grounding loss is the Joule heats consumed by grounding resistance, and small grounding resistance will lead to small grounding loss.

5. Summary and Conclusion

A conceptual superconducting DC cable model has been designed by using Ansoft/Maxwell soft in this paper, with its magnetic field distributions presented. The power transmission performance including power loss, DC and AC ground faults of HTS DC line and common DC line have also been studied and analyzed.

From the analysis, we can conclude that:

1) The HTS cable with CD configuration has a suitable magnetic performance and is feasible for practical application.

2) The HTS DC transmission system can be applied to lower the power losses. The total losses in the traditional DC transmission system are about two times of the losses in the HTS DC transmission system.

3) The dynamic performance of the HTS DC transmission system is matching that of the traditional DC transmission.

4) Applications of HTS technology to power system can provide a number of promising economical benefits, high reliability and high stability, especially for the low-voltage and large-current DC transmission.

References


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Jian-Xun Jin was born in Beijing, in 1962. He received B.S. degree from Beijing University of Science and Technology in 1985, M.S. degree from University of New South Wales, Australia in 1994, and Ph.D. degree from University of Wollongong, Australia in 1997. He was a research fellow and Australian ARC project chief investigator and senior research fellow with Australian University of Wollongong from 1997 to 2003. He is currently a professor and the Director of the Center of Applied Superconductivity and Electrical Engineering, UESTC. His research interests include applied high temperature superconductivity, measurement, control and energy efficiency technology.