The second cooling test of 1000-meter superconducting DC cable system in Ishikari

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\textsuperscript{1} Chubu University, \textsuperscript{2}Chiyoda Corporation, \textsuperscript{3} Sumitomo Electric Ind.Ltd., \textsuperscript{4} Ishikari Superconducting DC Power Transmission System (I-SPOT)
HTS DC power transmission system (Ishikari PJ) supported by METI (FY2013-2015)&NEDO(FY2016)

Connect PV and iDC by underground superconducting cable system
» DC-DC real operation test

1km-dc cable system (2.5kA, 50VA) for various testing
» To obtain data for future longer length (20km~) cable system
Key technical issues for realization of long distance HTS DC transmission system

» Low heat loss & low pressure drop LN₂ circulation
  – HTS DC cable loss almost depends on heat leak of the system.

» Releasing thermal contraction and expansion of SC cable during cooling/warming process
  – Thermal contraction ~ 0.3% ⇒ 3 m for 1km cable
    » Line tension of about 3 ton without release
    » Close to yield stress of strand former
### Specification of Ishikari -Line 2 (1000m)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Current</td>
<td>2500A</td>
</tr>
<tr>
<td>Transmission Capacity</td>
<td>50MVA</td>
</tr>
<tr>
<td>Length</td>
<td>1000m</td>
</tr>
</tbody>
</table>

### Line 2

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designed maximum current</td>
<td>2.5kA</td>
</tr>
<tr>
<td>Total number of inner conductor</td>
<td>24*1 (Ic≥4.3kA@77K)</td>
</tr>
<tr>
<td>Total number of outer conductor</td>
<td>15*2 (Ic≥3.3kA@77K)</td>
</tr>
<tr>
<td>Dielectric layer</td>
<td>PPLP®</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>40mm</td>
</tr>
</tbody>
</table>

*1 DI-BSCCO® (Type HT-CA (Ic>180A), Sumitomo Electric Industry
*2 DI-BSCCO® (New Type HT-CA (Ic>220 A), Sumitomo Electric Industry

- **Multi-joint**
  - Core-stop joint (CSJ)
  - Normal joint (NJ)
LN2 circulation system (Line 2 1000m)

**Refrigerators**
- 2 kW Turbo-Brayton refrigerator (Taiyo Nissan Sanso Co.)
- 1 kW Stirling refrigerator (AISIN)

**LN2 pumps**
- Centrifugal pump with magnetic bearing (AISIN)
- Bellows pump (Eagle Industry CO. LTD.)
① Low heat leak & Low pressure drop LN$_2$ circulation

Two types of smooth cryogenic pipe

**Normal type**

**With radiation shield**

Cable pipe

267 mm

318 mm

Normal Type

Section 2 : 125.0 m

Joint A
CSJ

Joint B
NJ

Normal Type

Section 1 : 468.8 m

Section 3 : 372.5 m

Helical deformation

Circulation Pump

Terminal B

Terminal A

Refrigerator Circulation Pump
Low heat leak: Peltier current lead

Heat leak vs. applied current measured for PCL installed in the present system using a test bench in Chubu Univ.

Heat Leaks for
Copper Lead ≈ 50W/kA
Pertier Current Lead < 30W/kA

S. Yamaguchi et al., Physica C 471, 1300 (2011)
S. Yamaguchi et al., Physics proccedia 36, 1131 (2013)
2. Against thermal contraction during cooling/warming
Movable terminal cryostat & Helical deformation technique

Helical deformation has been performed as follows.
1. Fix one side of the cable.
2. Cool down the cable to liquid nitrogen temperature

3. When the whole length of the cable become LN2 temperature, we fix other side of the cable.
4. Slowly warm up the cable to the room temperature

X-ray observation of cable after helical deformation

The helical periodicity \(Hp: 1250 \text{ mm} – 1900 \text{ mm}\)
\(Hp=1250 \text{ mm}\) is calculated to absorb 0.32% of thermal contraction.
Cooling test (2nd cooling test: July 19, 2016 – )

- N₂ gas flow: -160°C for about 40 hrs, then -170°C for about 4 hrs
- Injection of LN₂: after 49 hour, finished at 55 hour and started LN₂ circulation.

The temperature profiles of cable core surface measured by the optical fiber sensor during initial cooling process.
**Results**

1. **Low heat leak & Low pressure LN$_2$ circulation**

   ![Graph showing heat leak comparison between Nov. 2016 and Nov. 2015.](image)

   - **Section 2 Normal Type**
     - Total heat leak < 2 kW
     - Low heat leak < 1.5 kW (cable + return)
     - Radiation shield effectively decreases heat leak at cable pipe to 0.06 W/m.

   » 0.6 kW for 10km : $\Delta T=1.1$ K at 20L/min

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Results

Low heat leak & Low pressure circulation of LN2

Measured $\Delta P$ and the estimated $\Delta P$ for longer cable system

Low $\Delta P$: 11 kPa (cable pipe) and 18 kPa (return pipe) @ 32L/min

From estimation, $\Delta P$ is about 0.14 MPa & 20 L/min for 10 km.

This value is within the speculations of existing LN$_2$ pumps

Results

② Against thermal contraction during cooling/warming
Movable terminal cryostat & Helical deformation technique

Relationship between temperature and the axial tension of the cable core during the cooling process

Axial tension strength of the cable can be controlled below 1000 kgf.
The measured $I_c$ values have a good agreement with the estimated values from sample test. The $I_c$ properties were conserved after the cable laying and cooling process.

Inset: Temperature dependence of $I_c$ (criterion $0.1 \, \mu V/\text{cm}$). The broken lines show $I_c$ value estimated from the sample test of SC tapes for minimum and maximum $I_c$. 

I-V curve at 69.7 K
Results

Continuous current loading test

2.5kA x 3hrs

End-to-end voltage of HTS tapes

Heat loss estimated from the temperature rise

- Voltage of the tapes are below $I_c$ and stable during loading test
- Increase of heat loss with current loading is observed mainly in terminals.
- Almost negligible at SC cable sections and joints
Results

Stability of Cooling system

- Load cycle test of 1 kA-8 hrs + 0 A-16 hrs for 20 days
- 40 days operation test of circulation system (without current load) for about 1 month
  - confirmed the stability of the system.

- Ic, performance of cooling systems was confirmed to be unchanged before and after 5 months of operation tests.
  - Total operation time: TB refrigerators: 3320 hours, LN$_2$ pumps: 2310 hours
Summary

» Low heat loss and pressure drop for LN$_2$ circulation with our proposal system suggests 10 km system (unit length) is technically feasible.

» Helical deformation technique is effective to solve thermal extension and contraction problem of cable core

» Stable operation of the cooling system was confirmed during 20 days of load cycle test and long time operation test (40 days)
  • TB refrigerators:3320 hours
  • LN$_2$ pumps:2310 hours
Thank you for your attention!

This work was supported by METI & NEDO
Results

Load cycle test
(1 kA x 8 hours + 16 hours off) for 20 days

Enlarged view

※: Interruption of test occurred because of power out/malfunction

End-to-end voltage measured at SC tapes
Background

“Long-term Energy Supply/Demand Outlook“ METI says Japan needs more renewable energy sources!

==> Long length transmission system is necessary

Merits of superconducting dc transmission line

» Suitable for long length transmission
  – Low transmission loss = free of ac loss, zero resistivity, only heat loss
» Low building cost
» Environmentally friendly
  – No electromagnetic pollution
  – Low voltage

出典：http://www.amsc.com/