Long-Term Verification Test of a 275 kV-3 kA REBCO HTS Model Cable

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HTS Cable projects in the world

We can be available for any HTS cables with high current, high voltage, and DC.
Merits of 275 kV HTS cable

- The capacity of the 275 kV HTS cable having 1.5 GW corresponds to a typical overhead transmission line.
- The total loss of the 275 kV HTS cable becomes one-fifth of that of the XLPE / OF cable.

<table>
<thead>
<tr>
<th></th>
<th>XLPE cable 3cct</th>
<th>HTS cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rating voltage</td>
<td>275kV</td>
<td>275kV</td>
</tr>
<tr>
<td>Rating capacity</td>
<td>1,500MVA</td>
<td>1,500MVA</td>
</tr>
<tr>
<td>(3 circuit = 9 cables)</td>
<td>(1 circuit = 3 cables)</td>
<td></td>
</tr>
<tr>
<td>Current</td>
<td>1.05kA × 3</td>
<td>3.15kA</td>
</tr>
<tr>
<td>Transmission loss</td>
<td>284 kW/km</td>
<td>59 kW/km</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>φ155mm × 9</td>
<td>φ150mm × 3</td>
</tr>
</tbody>
</table>

- Compact

- Cable construction cost [×0.1B/km-cct]

- 53% decrease

- Conventional cable
- Superconducting cable
Development of 275 kV-3 kA HTS cable

Technical Targets:

(1) Low Loss:
   - AC loss and dielectric loss <0.8 W/m at 3 kA_{rms} and 275 kV

(2) Design of Electrical insulation:
   - cable, termination and joint
     (PD free at AC 310 kV, no BD at impulse 1155 kV)
     *[PD: Partial Discharge, BD: Breakdown]

(3) Endurance of over-current:
   - 63.0 kA_{rms} for 0.6 s;

(4) Compact:
   - <150 mm (outer diameter)

Ic: 300 A/cm at 77 K
Wire made by Fujikura/Showa and SRL

Technical Targets:

- HTS Shield
- Insulation
- HTS conductor

Cu (~25 μm)
Ag (~30 μm)
YBCO (~1.5 μm)
CeO₂ (~1.0 μm)
Gd₂Zr₂O₇ (~1.0 μm)

Hastelloy ~100 μm
structure of coated conductor (FJK)
Development contents

2008～2010:  **Fundamental technology and system design**
- AC loss reduction
- Over-current test
- Design of electrical insulation
- Design of the cable system

2011:  **Fabrication and Evaluation of Test Cable**
- Fabrication
- Evaluation (Ic, Withstand voltage test, over-current characteristics)

2012:  **Demonstration system**
- 275kV-3kA Cable fabrication
- Transportation (Japan→Shenyang, China)
- Installation (System construction)
- Verification test (Ic, AC current test, Withstand voltage test, AC loss and dielectric loss, Long-term verification test)
AC loss measurement

AC loss is reduced by using 3 mmW tape to suppress the perpendicularity field on the tape. Cutting method of tape has been improved to prevent damage of cutting part.

AC loss of the designed conductor was low, 0.124 W/m at 3kA.
Investigation of insulation material (275kV HTS cable)

To reduce dielectric loss, pp laminated paper with a higher pp ratio of 60% was used.
# Design of 275 kV-3 kA HTS cable

<table>
<thead>
<tr>
<th>Structure</th>
<th>Specification</th>
<th>Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Former</td>
<td>Hollow stranded copper</td>
<td>35.4</td>
</tr>
<tr>
<td>HTS conductor</td>
<td>2-layer YBCO</td>
<td></td>
</tr>
<tr>
<td>Insulation</td>
<td>PP laminated paper</td>
<td>81.0</td>
</tr>
<tr>
<td>HTS Shield</td>
<td>1-layer YBCO</td>
<td></td>
</tr>
<tr>
<td>Cu Protective</td>
<td>Copper tape</td>
<td>88.0</td>
</tr>
<tr>
<td>Protection</td>
<td>Insulation paper</td>
<td></td>
</tr>
<tr>
<td>Cryostat pipe</td>
<td>SUS and PVC sheath</td>
<td>150</td>
</tr>
</tbody>
</table>
275kV-3kA Cable fabrication

HTS core of 50 m

In VISCAS

HTS core with cryostat pipe

Cu hollow former
HTS conductor
Insulation
HTS Shield
Vacuum insulation
PE φ150mm

sample tests, Ic, over-current, withstand voltage tests.

30 m for demonstration
Testing condition

- Test conditions were decided as a shipping test and a long term verification test, referring to the conventional cable standards of IEC and JEC.

<table>
<thead>
<tr>
<th>Test</th>
<th>Shipping test</th>
<th>Long term verification test</th>
<th>Referenced standard</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1 Partial discharge test</strong></td>
<td>Sample cable of 5 m</td>
<td>30 m cable</td>
<td></td>
</tr>
<tr>
<td><strong>2 Critical current measurement</strong></td>
<td>DC</td>
<td>DC</td>
<td></td>
</tr>
<tr>
<td><strong>3 Load-cycle (Long-term verification test)</strong></td>
<td>200 kV-1 month</td>
<td>3 kA ON/OFF, More than 20 cycles</td>
<td>JEC-3408</td>
</tr>
<tr>
<td><strong>4 Critical current Dielectric loss</strong></td>
<td>DC</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>5 Impulse voltage</strong></td>
<td>± 1155 kV-3shots</td>
<td>After long term test ±1155 kV-3shots</td>
<td>JEC-3408</td>
</tr>
<tr>
<td><strong>6 Partial discharge test</strong></td>
<td>310 kV-10min</td>
<td>310 kV-10min</td>
<td></td>
</tr>
<tr>
<td><strong>7 Voltage test</strong></td>
<td>320 kV(2U₀) 15min</td>
<td>320 kV(2U₀) 15min</td>
<td>IEC62067</td>
</tr>
<tr>
<td><strong>6 Voltage test</strong></td>
<td>400 kV(2.5U₀) 30min</td>
<td>400 kV(2.5U₀) 30min</td>
<td>IEC62067</td>
</tr>
</tbody>
</table>
Long-term Characteristics (V-t)

Evaluation of the Long-term characteristics (V-t) of model cables with insulation thicknesses of 1 mm

V-t of PDIE and breakdown at 0.3 MPa(abs.)

<table>
<thead>
<tr>
<th>AC Voltage [kV/mm]</th>
<th>V-t of PDIE, n=80</th>
<th>V-t of AC breakdown stress, n=50</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Life time constant of PDIE was 80. There was no degradation after the V-t of PDIE.

Life time constant of B.D. was 50. There was degradation after the V-t of B.D.

Long-term verification test

\[ V_{\text{typeAC}} = U_0 \cdot \left(\frac{30\text{years} \cdot 365\text{days}}{30\text{days}}\right)^{\frac{1}{n}} \]

n (life time constant) = 50

U₀ = 160 kV

<table>
<thead>
<tr>
<th>Voltage</th>
<th>160 kV</th>
<th>200 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>term</td>
<td>30 years</td>
<td>30 days</td>
</tr>
</tbody>
</table>

0.3 MPa(abs)

42.3 kV/mm
65 h

760h
Sample tests (1) Ic, Over-current test

**Ic:**

Ic was obtained as 6440A at 77.3 K, almost agreed the sum of all the used YBCO tapes

\[ Ic = 6440 \text{A} \quad (@1\mu m/cm) \]

(Voltage tap distance: 1.5 m)

**Over-current test:**

At 63.0 kA_{rms} for 0.6 s, which was the worst situation in 275 kV systems

No Ic degradation after 63.0kA_{rms} for 0.6sec
Sample tests (2) voltage withstand tests

Detection of the PD inception stress

Sample cable

LN₂/ PP laminated paper

Cryostat for voltage tests

<table>
<thead>
<tr>
<th>Model cable Voltage test</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Voltage test</td>
<td>400kV 30min</td>
</tr>
<tr>
<td>Imp Voltage test</td>
<td>1155 kV</td>
</tr>
<tr>
<td>PD test</td>
<td>310 kV (no P.D.)</td>
</tr>
</tbody>
</table>

The sample was PD free at AC 310 kV for 10 minutes and withstood at AC 400 kV in LN₂ under atmospheric pressure.
Joint construction and Transportation

After Vs. Before
- Visual confirmation
- Acceleration

Comparison result:
There was no trouble during the transportation.
System construction (1)

Testing sites

Transformer

Terminal

XLPE cables for current carrying
System construction (2)

Cooling system

Monitoring

LN2 circulating in the closed loop, No cooler.
System construction (3)

Finished at October 2012

- Transformer
- Terminal
- Joint
- Cooling system house
- Cold Evaporator
- Control room
- Cooling system monitoring
- PD test monitor
- Voltage controller
- Current controller
System construction

- Joint & Termination
- 30 m HTS Cable
- Joint
- Cooling system house
- AC Transformer
Before long-term test

\[ \text{\( I_c \): 77.3k} \]

Conductor layer:
\[ 6800 \text{ A} \]

Shield layer:
\[ 7000 \text{ A} \]

**AC current test:** 3 kA\(_{\text{rms}}\)

The rate of shield current to conductor current is about 75%, which is due to 13 m long of the normal conduction part in the shield circuit according to the results of numerical calculation. The inductance of normal conductor is dominant. The shield rate of only HTS cable is 98.6%
Long-term test
(11/18~12/20)

<table>
<thead>
<tr>
<th>Operation Temperature</th>
<th>72 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling capacity</td>
<td>&gt;3 kW</td>
</tr>
<tr>
<td>Voltage</td>
<td>200 kV</td>
</tr>
<tr>
<td>Current</td>
<td>3 kA</td>
</tr>
<tr>
<td>Cycle</td>
<td>&gt;20 (8h ON, 16h OFF)</td>
</tr>
<tr>
<td>Term</td>
<td>1 month</td>
</tr>
</tbody>
</table>

Successfully conducted
200 kV- 1 month:
Determined by assuming insulation degradation in 30 years

Results of Verification test (2)
Results of Verification test (3)

After long-term test

PD test:

No-PD was observed at AC 310 kV for 10 minutes

Ic: No degradation

AC loss: 0.19 W/m  (measured by the calorimetric method)

Dielectric loss: 0.44 W/m at the operating voltage of 160 kV, which is almost 25% lower than the designed value of 0.60 W/m

Suggesting the superior reliability of this HTS cable system even for 30 years.
275kV-3kA HTS cable was designed and fabricated:

- HTS Cable outer diameter 150 mm
- Ic 6440 A at 77.3 K of the conduction layers of 1.5 m long part
- PD-free at 310 kV and No BD at 400 kV in LN$_2$ under atmospheric pressure
- No Ic degradation after the over-current of 63.0 kA$_{\text{rms}}$ for 0.6 s

Construction of demonstration system was completed:

- Included the 30 m long HTS cable, two terminals, a cable joint and a cooling system

Verification test:

- Ic of HTS conductor and HTS shield were 6800 A and 7000 A, respectively
- Long-term verification test was successfully conducted
- No-PD and No-Ic degradation after the long-term verification test

These results show a success in the development of 275kV-3kA HTS cable with the world's highest voltage and largest capacity