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

Shinichi Mukoyama, Masashi Yagi, Takaharu Mitsuhashi, Jin Liu (Furukawa Electric)
Takeshi Ohkuma, Osamu Maruyama (ISTEC-SRL)
Naoki Hayakawa (Nagoya Univ.)
Xudong Wang, Atsushi Ishiyama (Waseda Univ.)
Naoyuki Amemiya (Kyoto Univ.)
Takayo Hasegawa (Showa Cable Systems)
Takashi Saitoh (Fujikura)

This work was supported by the NEDO in M-PACC project.
We can be available for any HTS cables with high current, high voltage, and DC.
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><strong>Rating voltage</strong></td>
<td>275kV</td>
<td>275kV</td>
</tr>
<tr>
<td><strong>Rating capacity</strong></td>
<td>1,500MVA</td>
<td>1,500MVA</td>
</tr>
<tr>
<td></td>
<td>(3 circuit = 9 cables)</td>
<td>(1 circuit = 3 cables)</td>
</tr>
<tr>
<td><strong>Current</strong></td>
<td>1.05kA × 3</td>
<td>3.15kA</td>
</tr>
<tr>
<td><strong>Transmission loss</strong></td>
<td>284 kW/km</td>
<td>59 kW/km</td>
</tr>
<tr>
<td></td>
<td>～1/5</td>
<td></td>
</tr>
<tr>
<td><strong>Outer diameter</strong></td>
<td>φ155mm × 9</td>
<td>φ150mm × 3</td>
</tr>
</tbody>
</table>

- Compact
Development of 275 kV-3 kA HTS cable

**Technical Targets:**

(1) **Low Loss:**
- AC loss and dielectric loss
- $<0.8 \text{ W/m at } 3 \text{kA}_{\text{rms}} \text{ and 275 kV}$

(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:**
- $63.0 \text{kA}_{\text{rms}}$ for 0.6 s;

(4) **Compact:**
- $<150 \text{ mm (outer diameter)}$

I$_c$: $300 \text{ A/cm at 77 K}$
Wire made by Fujikura/Showa and SRL

**Structure of coated conductor (FJK):**
- Cu (~25µm)
- Ag (~30µm)
- YBCO (~1.5µm)
- CeO$_2$ (~1.0µm)
- Gd$_2$Zr$_2$O$_7$ (~1.0µm)
- Hastelloy ~100µm

**Insulation:**
- HTS Shield
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.

The calculation: taking Jc distribution into account

AC loss of the designed conductor was low, 0.124 W/m at 3kA.
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

All Rights Reserved, Copyright© FURUKAWA ELECTRIC CO., LTD. 2013
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>1 Partial discharge test</td>
<td>310 kV-10min</td>
<td>310 kV-10min</td>
<td></td>
</tr>
<tr>
<td>2 Critical current measurement</td>
<td>DC</td>
<td>DC</td>
<td></td>
</tr>
<tr>
<td>3 Load-cycle (Long-term verification test)</td>
<td>200 kV-1 month 3 kA ON/OFF More than 20 cycles</td>
<td>JEC-3408</td>
<td></td>
</tr>
<tr>
<td>4 Critical current Dielectric loss</td>
<td>DC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Impulse voltage</td>
<td>± 1155 kV-3shots</td>
<td>After long term test ±1155 kV-3shots</td>
<td>JEC-3408</td>
</tr>
<tr>
<td>6 Partial discharge test</td>
<td>310 kV-10min</td>
<td>310 kV-10min</td>
<td></td>
</tr>
<tr>
<td>7 Voltage test</td>
<td>320 kV(2U₀) 15min</td>
<td>320 kV(2U₀) 15min</td>
<td>IEC62067</td>
</tr>
<tr>
<td>6 Voltage test</td>
<td>400 kV(2.5U₀) 30min</td>
<td>400 kV(2.5U₀) 30min</td>
<td>IEC62067</td>
</tr>
</tbody>
</table>
Evaluation of the Long-term characteristics (V-t) of model cables with insulation thicknesses of 1 mm

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.
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.

![Graph showing Ic=6440 A (at 1μm/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 0.6 sec
Sample tests (2) voltage withstand tests

Detection of the PD inception stress

<table>
<thead>
<tr>
<th>Sample tests (2) voltage withstand tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model cable Voltage test</td>
</tr>
<tr>
<td>AC Voltage test</td>
</tr>
<tr>
<td>Imp Voltage test</td>
</tr>
<tr>
<td>PD test</td>
</tr>
</tbody>
</table>

The sample was PD free at AC 310 kV for 10 minutes and withstood at AC 400 kV in LN$_2$ under atmospheric pressure.

Model cable Voltage test

AC Voltage test 400kV 30min
Imp Voltage test 1155 kV
PD test 310 kV (no P.D.)
Joint construction and Transportation

Comparison result:
There was no trouble during the transportation.

After Vs. Before
✓ Visual confirmation
✓ Acceleration

Terminal
Cable joint
HTS Cable

Chiba, Yokohama
Shenyang
Dalian
China
Japan
System construction (1)

Testing sites

Transformer

Terminal

XLPE cables for current carrying
Monitoring

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

Finished in October 2012
System construction
Before long-term test

$I_c$: 77.3K

Conductor layer:
- 6800 A

Shield layer:
- 7000 A

AC current test:

$3 \text{kA}_{\text{rms}}$

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%
Results of Verification test (2)

Long-term test
(11/18~12/20)

Successfully conducted

<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>

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

[Graph showing Voltage and Current over time]
Results of Verification test (3)

After long-term test

PD test:

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

\[ |C|: \text{No degradation} \]

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.
Summary

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 LN₂ under atmospheric pressure
- No Ic degradation after the over-current of 63.0 kA_{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