Live-Grid Operation and Maintenance of the 35 kV/121 MVA Superconducting Cable System

Huan-Huan Li, An-Lin Ren, Ying Xin, Hui Hong, Zhi-Li Chen, and Lin-Na Shi

Abstract—A 33.5 m, 35 kV/121 MVA, three-phase, warm dielectric HTS power cable system was successfully installed and activated in China Southern Power Grid at the Puji substation in Kunming on April 19th of 2004, supplying electricity to four industrial customers (including two metallurgical refineries) and a residential population of about 100000. In this paper, we give an update on the operation and maintenance status of the system and comments on reliability issues. We conclude that the superconducting cable system is currently quite robust and feasible for particular utility applications, and it will be improved by advancement in cryogenic equipment and system technology.

Index Terms—Power grid, power transmission, superconductivity, superconducting cable.

1. Introduction

Discovered in 1911, the phenomenon of superconductivity occurs when materials are cooled to extremely low temperatures and their electrical resistance disappears. The disappearance of resistance makes it possible to avoid the energy loss associated with electricity transmission. Logically, the use of a superconducting cable to reduce energy loss in an electrical network is one of the direct applications of superconductivity technology, however, it was not practically feasible until the discovery of the high temperature superconductors (HTS), which only requires cooling with liquid nitrogen (LN\textsubscript{2}) (at minus 196°C).

Superconducting cables can increase power handling capability and efficiency without requiring additional right-of-way or trenching in areas that need additional power. They can help simplify the electrical infrastructure due to the fact that they are able to transmit massive current, which can be further utilized to reduce the number of voltage levels (fewer transformer substations).

Since the first HTS cable project started in the United States in 1992\cite{1}, R&D programs on HTS cable technology have been undertaken in many countries around the world. A single superconducting cable with a length of 500 meters has been manufactured and tested in Japan\cite{2}. Superconducting cable systems have been installed in real power transmission networks in the world since 2001\cite{3,4,5,6}. Partially funded by the Chinese government, our power cable project begun in 2002 and the live-grid operation of a 35 kV/121 MVA superconducting cable system was launched at Puji Substation of China Southern Power Grid in 2004.

2. System Description

As shown in Fig. 1, this cable system consists of three 33.5 m 35 kV individually packaged warm-dielectric cables that make up the three electrical phases, six terminations, a closed cycle LN\textsubscript{2} cooling station, the cryogenic system control unit, and the real-time monitoring and protection system for live-grid operation. The three phases are installed in parallel, 850 mm apart, with a 90° bent angle. The cables were set on the supporting frames whose height is 750 mm.

![Fig. 1. The circuit diagram of the 35 kV/121 MVA superconducting cable system at Puji substation.](image-url)

The cables replaced part of the substation bus and linked a 220 kV/110 kV/35 kV step-down transformer to outgoing overhead lines, distributing electricity to four industrial customers (including two metallurgical refineries) and a residential population of about 100000.
Fig. 2. Bird’s-eye view picture of the installation.

3. System Commissioning

3.1 Review Stage

After the installation, we carried out a series of field tests, including dc resistance, electrical insulation, thermal insulation, ac voltage withstanding, and through-current capacity tests. For the cable’s through-current capacity test, we shorted the three ends of the cables on one side and powered each phase of the three phases on the other side. The current source was from boost converters that were connected to the grid through voltage-regulating transformers. Six boost converters and four voltage-regulating transformers were used for each phase.

In this test, the initial current was 100 A. Then the current was increased by an increment of 200 A for each step up to 1500 A. The current was held at 1500 A for two hours and then raised to and held at 2000 A for 35 min. At each step, we measured the voltage and the phase angle of each phase. The test results showed that the system was able to carrying ac 2000 A without any signs of quench.

Some field test results are summarized in Table 1.

Table 1: Field test results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC resistance (cable + terminations, at ambient temperature before system cooling down)</td>
<td>10.6 mΩ (Phase A), 10.1 mΩ (Phase B), 10.2 mΩ (Phase C)</td>
</tr>
<tr>
<td>DC resistance (cable + terminations, at 74 K of cable conductor after system cooling down)</td>
<td>85 µΩ (Phase A), 84 µΩ (Phase B), 84 µΩ (Phase C)</td>
</tr>
<tr>
<td>DC resistance of a termination (at 77 K, factory)</td>
<td>40 µΩ</td>
</tr>
<tr>
<td>Phase shift between I and V (at 50 Hz, 1500 A, 74 K)</td>
<td>83.0° (Phase A), 84.6° (Phase B), 85.1° (Phase C)</td>
</tr>
<tr>
<td>AC loss (at 50 Hz, 1500 A, 74 K)</td>
<td>26-30 W/phase</td>
</tr>
</tbody>
</table>

3.2 Commissioning

On April 19, 2004, the system was activated in the 35 kV live-grid at a transmission current of about 600 A. Since the maximum current of the transformer’s 35 kV outlet was 1350 A, in order to test the actual operating performance of the cable system at the level close to the rated capacity, the substation central control diverted more power through the bus from another transformer of the station to go through our cables. The total load of the two transformers at the 35 kV outlets was in the range from 1600 A to 1700 A during the 90 min test period. The superconducting cable system operated faultlessly in the full load test run.

After the full load test, the central of the substation returned 35 kV lines to normal operation mode. The superconducting cable system formally started its live-grid operation.

Table 2 and 3 list the key specifications and operation parameters of the cable system[10]—[12].

Table 2: The parameters of cables and terminations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
<td>35 kV</td>
</tr>
<tr>
<td>Rated current</td>
<td>2 kA</td>
</tr>
<tr>
<td>Operation temperature</td>
<td>74 K – 78 K</td>
</tr>
<tr>
<td>Operation pressure</td>
<td>40 kPa – 100 kPa</td>
</tr>
<tr>
<td>Operation current</td>
<td>450 A – 950 A</td>
</tr>
<tr>
<td>Ac loss</td>
<td>&lt; 1.0 W/single phase</td>
</tr>
<tr>
<td>Heat load of electrical lead</td>
<td>&lt; 45 W/kA</td>
</tr>
<tr>
<td>Operation thermoelectric of termination electrical lead</td>
<td>70 K – 310 K</td>
</tr>
<tr>
<td>Loss of one termination</td>
<td>&lt; 120 W</td>
</tr>
</tbody>
</table>

Table 3: The parameters of cryogenic system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigeration power</td>
<td>2000 W/70 K</td>
</tr>
<tr>
<td>Temperature of LN$_2$ entry</td>
<td>74 K – 77 K</td>
</tr>
<tr>
<td>Temperature of LN$_2$ exit</td>
<td>75 K – 78 K</td>
</tr>
<tr>
<td>Working pressure of heat exchange cryostat (gauge pressure)</td>
<td>–0.06 MPa – 0.14 MPa</td>
</tr>
<tr>
<td>Flow rate of LN$_2$ (L/h)</td>
<td>Phase A800-1000, Phase B/C400-500</td>
</tr>
<tr>
<td>Working pressure of LN$_2$ pump box (gauge pressure)</td>
<td>0.14 MPa</td>
</tr>
<tr>
<td>Temperature of cooling water</td>
<td>15°C – 37°C</td>
</tr>
<tr>
<td>Operation thermoelectric of termination electrical lead</td>
<td>70 K – 310 K</td>
</tr>
<tr>
<td>Loss of one termination</td>
<td>&lt; 120 W</td>
</tr>
</tbody>
</table>

4. Operation and Maintenance

4.1 Operation Instructions and Regulations

For safe and effective operation of the 35 kV/121 MVA superconducting cable system, following the codes and regulations applied to the electrical power transmission industry and with the help of the utility operators, we set up instructions for operation and maintenance, as well as creating some new regulations. These instructional and regulation documents mainly include:

1) Technical instructions of the 35 kV/121 MVA superconducting cable system;
2) Operation and maintenance regulations of the 35 kV/121 MVA superconducting cable system;
3) Examination and repair instructions of the control and protection system;
4) Abnormality and obstruction removal instructions of the control and protection system;
5) Examination and repair instructions for terminations;
6) Launching operation instructions of the cryogenic system;
7) Examination and repair instructions of the cryogenic system;
8) Examination and repair instructions of the cryogenic system control unit.

These documents regulated operation and maintenance procedures, failure and obstruction removal measures, personnel requirements, security, responsibilities of the cable operator, and so on.

### 4.2 Protection Strategy

To protect the superconducting cable system and the operation of the substation in case of a major power system incident or cable malfunction, there is in place a protection system to remove the superconducting cables from service and switch to the conventional line for maintaining the loads. Three levels of system protection are set up to protect the integrity of the system.

For the first level of protection, there are sensory devices that continually monitor cable temperatures, pressures, and LN$_2$ flows, alerting the main control if any of these parameters indicate unusual operation or problems in the cable system. The typical response to cable malfunctions would be to close the conventional line that runs parallel to the superconducting cable and break off the superconducting cable. This process requires less than 0.5s.

The second level of protection protects the superconducting cables from over-heating from current overload resulting from fault. During these cases, the current through the cable system is greater than the critical current of the superconducting but much lower than the rated maximum allowable fault current. Therefore, the cables can operate for some limited period of time before too much heat energy is accumulated in the cables and damage occurs. To maintain operation as long as possible, the protection system calculates the amount of heat energy and compares that value to a set threshold. When the calculated value surpasses the threshold, the cables will be isolated from the system.

The third level of protection isolates the superconducting cable system immediately when large fault currents are detected. The cable is designed to withstand fault current of 20 kA$_{rms}$ for up to 2 s.

### 4.3 Routine Operation

Operation of the cable system is automatically controlled. All operation parameters can be measured and a visual feed of the cable system can be monitored in real time at the central control room of the substation. As a precautionary measure, it is required that the substation worker on duty visits the cable three times a day, inspecting all meters and machines in the cryogenic station and filling out the daily recording log.

The parameters monitored at the cryogenic system control unit include 17 temperature points, 6 pressure points, 3 liquid height points and 4 LN$_2$ flow points. The substation worker on duty records the readings on the meters and compares them with the display values on the monitoring computer. When any value exceeds the normal range, the worker should check the records carefully and make the proper adjustments and/or report according to the rules and instructions.

Furthermore, we can analyze the data conveniently, which has been recorded by the appropriate software in the system. Afterwards, the analyzed data become the basis for researching different operating states of the system. The statistic and analytic software offers many functions, such as basic parameter calculation, waveform analysis, and on-off control analysis.

### 4.4 Performance of the System

We installed 7 refrigerators with a total cooling capacity of over 2000 W at 75 K. Usually, the cooling load is not more than 1000 W, and only 3 or 4 refrigerators are needed. The other coolers are prepared as back-ups. This set-up guarantees uninterrupted operation even if repair or maintenance work needs to be done on some of the machines and improves the reliability of the system.

The superconducting cables have had no any fault to date. It should be mentioned that at each routine maintenance we measured the dc resistance of the cable and terminations at ambient and LN$_2$ temperatures and the electrical insulation. There has been no any degradation observed of these parameters so far. The status of the terminations has also been satisfactory except for mechanical damage on the joint between the cryogenic coupling and the epoxy LN$_2$ pipe due to the thermal contraction and expansion during cryogenic system breakdown. The cable’s control and protection system has worked well.

As the first live-grid superconducting cable system in China, our system has delivered more than 300 MWh of electricity to customers and will keep operating for at least two more years. The annual growth of electricity delivered by the cable system is about 15%.

### 4.5 Improvement, Maintenance, and Repair

The four major breakdowns that the 35 kV/121 MVA superconducting cable system has experienced since it was commissioned came from the cryogenic system. The first one was a water blockage in the cooling coils of the refrigerator’s compressors. It was cause by the high CaO concentration in the tap water at the substation. To solve the problem, we replaced the open-cycle tap water supply with two closed-cycle soft water machines. The performance of the cooling water was greatly improved. However, after two years of operation, the circuit board of the closed-cycle cooling water machine broke, causing a system wide breakdown. Another breakdown was caused by a malfunction of the LN$_2$ flow rate gauge which resulted in a system operation failure. The final breakdown was due
to a tear-down of the bearing of the LN\textsubscript{2} pump. After the incident, we replaced the bearing every year.

Scheduled maintenance has been carried out at a frequency of about six months. The routine maintenance procedure includes replacement of the pump bearings, pressure checks of the refrigerator’s compressors, and vacuum checks on the cables and termination cryostats. Helium gas recharging was required one time for one of the seven compressors during the four-year period. Re-evacuation was performed one time on the cryostats of the terminations during this period.

5. Summary

Our 35 kV/121 MVA superconducting cable system is not flawless, but in general it is a successful application of new technology. Except for the routine maintenance and the reported breakdowns, the cable system has been in operation continuously during the past four years.

As a whole, we conclude that the superconducting cable system is quite robust and feasible for particular utility applications, although it could be improved by advancement in cryogenic equipment and system technology.

The power utility industry is poised for growth with an ever increasing global demand for electricity. With an estimated 80000 miles of underground cables throughout the world, superconducting cables can potentially provide an immense benefit to the utility industry and consumers. Besides being able to save energy, the use of superconducting cables also has striking economic and system advantages over conventional above-ground and below-ground transmission cables, such as higher power density, near zero environmental impact, and higher operating efficiency.

We will make the best use of the live-grid operation of the 35 kV/121 MVA superconducting cable system to further investigate this new technology. Improving design standards and operation regulations of superconducting cables are our most important work ahead.

References


Huan-Huan Li was born in Jiangxi Province, China, in 1981. She received the B.S. degree from the Northern Jiaotong University, Beijing, in 2003 and the M.S. degree from Beijing Jiaotong University, Beijing, in 2006. She is now working in Innopower Superconducting Cable Co., Ltd. Her research interest is in the electrical application of the superconducting.

An-Lin Ren was born in Hebei Province, China, in 1969. He received the B.S. degree from the Tianjin University, Tianjin, in 1991. He is now working in Innopower Superconducting Cable Co., Ltd. Her research interest is in the electrical application of the superconducting.

Ying Xin was born in Heilongjiang Province, China, in 1953. He received the B.S. degree from Tianjin University, Tianjin, in 1991, and the Ph.D. degree from University of Arkansas, in 1991. He is now working in Innopower Superconducting Cable Co., Ltd. Dr. Xin is active in high temperature superconductivity.

Hui Hong was born in Guangxi Province, China, in 1979. He received the B.S. degree from the Zhejiang University, Hangzhou, in 2001 and the Ph.D. degree from the Chinese Academy of Sciences, Beijing, in 2006, both in refrigerant and cryogenics. He is now working in Innopower Superconducting Cable Co., Ltd. His research interests include the electrical application of the superconducting.

Zhi-Li Chen was born in Hebei Province, China, in 1980. She received the B.S. degree from the Zhejiang University, Hangzhou, in 2001 and the M.S. degree both in electric power engineering and management from North China Electric Power University, Beijing, in 2002 and 2005, respectively. She is now working in Innopower Superconducting Cable Co., Ltd. Her research interests include application and development of HTS cable.

Lin-Na Shi was born in Beijing, China, in 1985. She graduated from Beijing Huijia University of International in 2006. She is now working in Innopower Superconducting Cable Co., Ltd. Her research interest is in the electrical application of the superconducting.