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TYPE TESTING OF A 13.2 KV, 69 MVA TRIAX HTS CABLE

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ABSTRACT

A Tri-Axial high-temperature superconducting cable system was type tested in preparation for installation in the utility grid in Columbus, OH, in the United States. The cable and accessories were designed for a 15 kV-class voltage with a nominal current of 3000 A. The testing procedure was compiled from applicable parts of existing norms for XLPE cables and oil-filled, paper-insulated cables and approved by the utility customer, American Electric Power Co., AEP. Additional procedures were added for the cryogenic components of the system. This article describes in detail the testing procedure that led to the approval of this cable design.

KEYWORDS

High temperature superconductor, superconducting, cryogenic, dielectric, cable, type testing, underground.

INTRODUCTION

Several installations worldwide are now demonstrating high-temperature superconducting cables. This article describes the type-testing in preparation of a 2-year test installation of a 13.2 kV, 69 MVA Triax cable for the American Electric Power Co (AEP) in Columbus, Ohio.

High-Temperature Superconducting power cables (HTS cables, “supercables”) can carry three to five times more power at every voltage level with lower energy losses and less voltage drop than conventional copper- or aluminum power cables. This allows for new system solutions in urban areas.

The practical reach of MV (10-35 kV) is extended from 1-10 km to 10-200 km. This allows for a reduction of the number of substations in a meshed network. What is today transmission and sub-transmission at 50-400 kV can be carried out at lower voltage levels.

Since the HTS technology is now at its entry-stage with small manufacturing volumes, the costs are initially high compared to the conventional alternatives. Therefore, the first uses will be where large civil-engineering and environmental savings can be made. Such early uses include the retrofit of cables in existing ducts and tunnels, upgrading of the power rating in a narrow rights-of-way, and the out-localization of HV substations away from sensitive or congested areas.

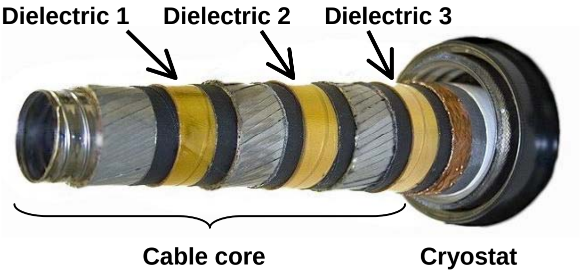

Figure 1: Triax superconducting cable.

TYPE TESTING

Background

There is not yet an established norm for the type testing of HTS cables. A test procedure was compiled based on applicable parts of existing norms [1-7] and additional tests based on the experiences of previous HTS cable installations [8, 9]. The type tests were carried out on 3-5 m long samples in preparation for a 200 m long pilot installation [10-13].

The electrical insulation consists of a lapped polymer ribbon (Cryoflex™) in multiple layers impregnated by liquid nitrogen at a temperature of 68 K to 83 K (-205 C to -190 C) and pressurized to 3-6 barg. This means that high-voltage tests of practical cables longer than a few meters require a complete system consisting of cable conductor, thermal insulation and pressure containment (“cryostat”), terminations and a cooling system.

The type tests were separated in three different parts as follows:

1) Type tests on a 5 m cable system;
2) Fault-current tests on 3 m cable and splice samples;
3) HV tests on 3 m splice samples.

Type tests on a 5 m cable system

Many of the testing procedures were carried out on a 5-m test system consisting of a flexible 5 m cable, terminations and a cooling system. The tests were carried out at ORNL.

Figure 2: 5 m test system at ORNL.

Room-temperature tests

At the start, the resistances of the phase conductors and the neutral conductor were measured at room-temperature. This is to ascertain the volume of materials installed and the quality of the connections.

Cryogenic tests

The cable system was cooled to 77 K, approximately 25-33 K below the critical temperature of the superconductor. Then the residual resistances of the phase conductors and of the neutral conductors were measured. This resolves the resistances of the current leads.

The system was then pressurized and checked for leaks. The pressure was then cycled between minimum and maximum operating values, and the system was again checked for leaks.

DC current tests

The temperature was adjusted to 79 K, corresponding to the warm end of a long cable system. The critical current of each phase conductor was measured using a 1 µV/cm criterion. The current was increased from zero to 8000 A in steps of 50 A. The DC voltage was measured using a nano-volt meter. The linear part of the voltage was explained by the resistance of the current leads (Fig. 3). The non-linear part determines the critical current of each phase conductor (Fig. 4).

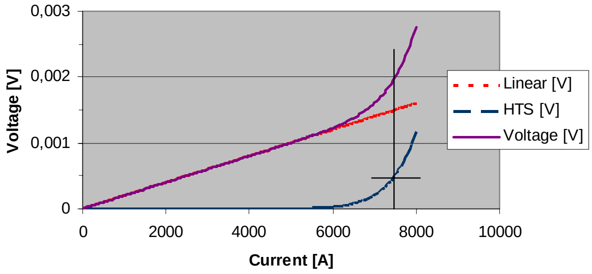

Figure 3: Schematic of a typical DC voltage test [10].

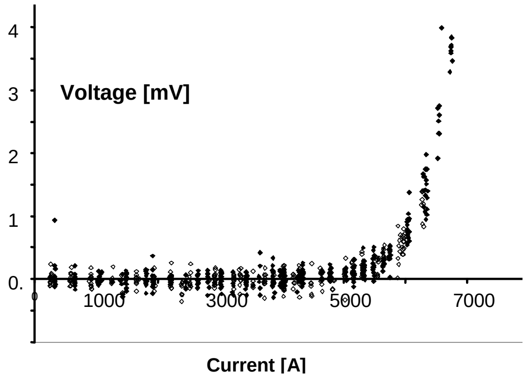

Figure 4: Current-voltage curve for phase 1 [12].

AC current tests at 60 Hz

Hysteresis losses in the superconductor generate electrical losses in a superconducting cable, so called AC losses. This loss is measured electrically in single-phase configuration. It is measured calorimetrically in three-phase configuration by measuring the temperature increase of the coolant flowing through the cable with and without current through the phases.

The calorimetric method is slower than the electricl method and therefore fewer measurement points are selected. The loss was measured at the following RMS AC currents at 60 Hz: 1000A, 1500 A, 2000 A, 2500 A, 3000 A, 3400 A.

The measurements were made first for one phase at a time and then for three-phase currents. This yields the AC loss per meter of the cable which enters in the design of the cooling system.

An extended run for 24 hours at 3000 h was used to prove the thermal stability of the conductor. The temperature of the conductor approaches a stable value.

Single-phase voltage stability

The HV tests were organized in order of increasing risk for breakdown [10]. Firstly, 7.6 kVrms phase-ground was applied for 1 h to phases 1, 2, and 3, one at a time. Then, a three-phase voltage of 13.2 kVrms phase-phase was applied with the neutral connected to ground on both sides.

AC withstand (Cable specification)

All but one phase onductor was connected to ground. A voltage of 39 kVrms was applied to one phase conductor for 5 minutes. The voltage was increased from 6.25 kV in steps of 2.56 kV, 5 minutes per step.

BIL

The Basic Insulation Level for 15 kV operation is 110 kV. It is tested with ten positive and ten negative impulses during 40-60 µs. The impulses were applied to one phase-conductor at a time. In this way, some of the dielectrics were exposed to +20/-20 impolses or more without failure.

PD measurement (Termination specification)

PD measurements were made after the BIL tests. A voltage of 15.6 kV was applied to one phase at a time with the other phases and the neutral on ground. The PD was below 4 pC.

AC withstand (Termination specification)
A 50 kVrms phase-ground voltage was applied for 1 minute to each of the phase conductors with the other phases and neutral on ground. The voltage was ramped from 37 kV to 50 kV in 10-30 seconds and the PD value was recorded.

Thereafter, a voltage of 35 kVrms was applied in the same way for 6 hours, while recording the PD value. The voltage was ramped from 26 kV to 35 kV in 15-30 seconds.

Repeat of PD measurement
The PD measurement at 15.6 kV was repeated on each of the three phases. With a PD below 4 pC, it is concluded that the cable system is not critically damaged or degraded by the previous tests.

DC fault-current test
The specified worst-case fault currents were 20 kArms for 250 ms. This corresponds to a fault in the bus-work in the station and failure of the primary protection relays. The thermal effects of such a fault could be simulated in the 5 m system by exposing it to single phase DC currents of 10 kA for 1.0 seconds [11]. This test primarily focus on the thermal effects in the copper parts of the terminations.

Tests on cable bent to 90°
The following tests were repeated with the cable bent 90°: Critical current; HV withstand; BIL, and; DC fault currents.

Fault-current tests on 3 m samples

Several 3 m long cable samples were manufactured, and two of them were spliced together. Tests were made on these 3 m Triax samples and on the three-phase cable splice.

DC current tests of splice
The cable splice was immersed in open-bath liquid nitrogen at 77 K. The critical currents were measured for each phase conductor.

AC fault-current test of splice
The cable splice was again submerged in liquid nitrogen and soaked for half an hour. The splice was connected to a three-phase fault-current source as described in Fig. 5. It was exposed to three-phase currents with amplitudes of 10 kArms, 21 kArms, and 24 kArms for 250 ms, 500 ms and 750 ms. Shorter pulses with peak currents exceeding 60 kA were also used. The temperature of the conductor did not increase more than 10 K during any of these tests. Fig. 6 shows current and voltage traces for one of these tests.

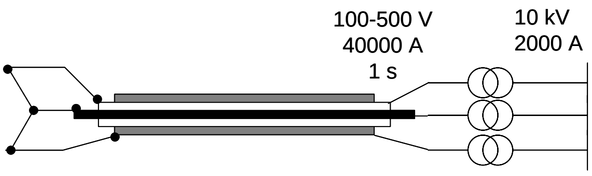

Figure 5: Three-phase fault-current test setup with 3 m samples.

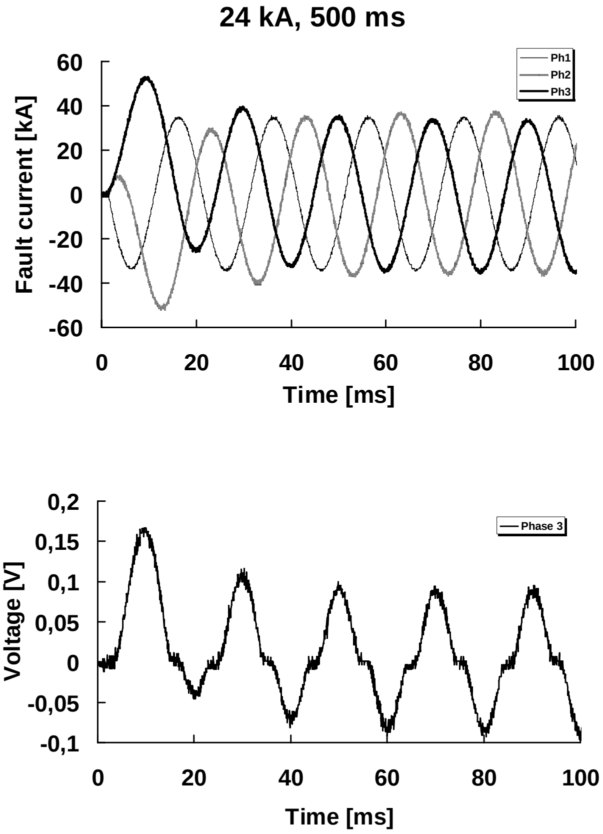

Figure 6: Three-phase fault test data showing currents through phases 1-3 and the voltage over phase 3.

HV tests on 3 m splice

A splice prototype was cut down to a length of 1.5 m in order to fit into an available test chamber with pressurized, sub-cooled liquid nitrogen. BIL tests with positive and negative pulses of 110 kV amplitude were applied until a total number of ten of each type had been accumulated without flash-overs or break-down.

IMPLICATIONS FOR LONGER SYSTEMS

Pressure drop

The pressure drop will be an important factor in systems longer than one km. Consequently; additional tests are required to determine the flow resistances in the cable and cryostat with high precision.

Temperature gradients

In longer systems, the temperature may vary significantly from on location to another. Here, the tests are performed at temperatures in the range of 77-79 K, corresponding to the “worst-case” warmest location of a cable. In order to accurately engineer a system, loss and flow values are needed in the range of 65-82 K.

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Cooling systems

The cooling stations are an integer part of the cable systems in terms of efficiency and reliability. For longer systems, larger pressure drops will pose demands on the puping systems as well as the active cooling machines. Additional test procedures are required for these components.

CONCLUSIONS

In spite of the lack of available norms for the testing of HTS power cables, it was possible to compile a test sequence that was accepted by the utility customer for installation of the MV HTS Triax cable in a public grid.

The cold-dielectric design requires a complete system with cable, terminations and a cooling system in order to withstand HV testing. This means that the testing procedure is relatively expensive. Two actions were taken as a consequence of this: 1) Single-phase modules of the terminations were tested to the type-test specifications before the three-phase system was built; 2) The test procedures were performed in order of increasing risk, so that the maximum amount of information can be obtained from a test system before a break down.

The test system survived the full type test without failure. The adequacy of these testing procedures will be verified by the ongoing two-year test. For long-length system approvels, additional tests are required that quantify the pressure drops and that qualifies the cooling station components.

ACKNOWLEDGEMENTS

This work was sponsored under U.S. Department of Energy, Office of Electric Transmission and Distribution, Superconductivity Program for Electric Power Systems. A large part of the HV, DC and AC type testing was carried out by Jonathan Demko, Isidor Sauers, Randy James and Mike Gouge at Oak Ridge National Laboratory under contract No. DE-AC05-00OR22725 with UT-Battelle, LLC. AC loss and thermal stability development tests were carried out at the Danish Technical University under the supervision of Prof. Ole Tønnesen. 50 Hz AC fault-current testing was carried out at the Electrotechnical Department,
Engineering College of Copenhagen under the supervision of Prof. Ib Kledal.

GLOSSARY

HTS: High Temperature Superconductor
ORNL: Oak-Ridge National Laboratory
IKT: Engineering College of Copenhagen, Ballerup

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