AMPACITY PROJECT – UPDATE ON WORLD'S FIRST SUPERCONDUCTING CABLE AND FAULT CURRENT LIMITER INSTALLATION IN A GERMAN CITY CENTER

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ABSTRACT

In recent years significant progress has been made in the development of high temperature superconducting (HTS) power devices. Several field tests of large scale prototypes especially for cable and fault current limiter applications have been successfully realized and the technologies are getting closer to commercialization.

This paper will give an update on the German AmpaCity project. The overall system design will be introduced and the type test results of the cable and accessories will be reported. Furthermore, the installation of the complete HTS system on site in Essen as well as its commissioning will be highlighted.

INTRODUCTION

In most European countries the power supply within cities is predominantly ensured through high, medium and low voltage power cables. A large fraction of these cables as well as the associated substations are approaching the end of their lifetime and therefore need to be refurbished in the upcoming years. Usually, old power devices will be simply replaced by new ones, and if there are major load changes, substations will be adapted by up- or downgrading.

The application of medium voltage HTS systems consisting of a concentric three phase HTS cable connected in series with an HTS fault current limiter (FCL) offers attractive alternatives to conventional systems. Replacing conventional high voltage cable systems by medium voltage HTS systems exhibiting the same power rating enables a considerable reduction of the number of inner city substations. Since HTS cables are in general more compact than conventional cables, the required right of way is much smaller and the installation is easier. Moreover, there are many other advantages of HTS cables. Besides the increased power density there is no thermal impact on the environment. In addition, HTS cables do not exhibit outer magnetic fields during normal operation and in combination with HTS fault current limiters the operating safety in the grid is increased as a result of reduced fault current levels.

Over the last few years, high temperature superconductors have matured, especially due to the technical progress achieved in manufacturing these materials, and they are getting closer to industrial scale production. Furthermore, several superconducting cable systems [1-5] as well as superconducting fault current limiters [6-8] for power systems have been tested in real grid applications worldwide and the transition to commercial projects is in progress. The experience gathered in the field tests shows that all technical requirements are fulfilled so far, and a high reliability of these new power devices can be achieved. At present, the main reason preventing wider use of the HTS technology is the higher capital cost compared to conventional devices. However, already today an economic advantage of the HTS technology can be realized wherever positive secondary effects are present. Regarding the design of electricity distribution networks, this would mainly include higher power density and space savings especially in congested urban areas.

Between December 2009 and December 2010 a feasibility study had been conducted under guidance of the Karlsruhe Institute of Technology (KIT) on behalf of the German utility RWE [9,10]. Together with superconductor cable and fault current limiter specialists from Nexans as well as other partners, it was investigated whether the electric power supply with medium voltage superconductor systems in city centers offers technical and economical advantages compared to conventional high voltage technology. The German city Essen was chosen for the study and the key result is, that four out of ten 110/10 kV transformer substations become dispensable in the downtown area by using 10 kV cable systems. Conventional 10 kV cables do not constitute a viable alternative because of the large routing requirements and the high losses involved. In comparison to 110 kV cables, 10 kV HTS systems allow a much simpler grid structure, which requires less space for cable routing and smaller areas for equipment installations. In addition, the grid with 10 kV HTS systems exhibits lower overall costs than the grid with conventional 110 kV systems.

Subsequent to the positive results of the feasibility study RWE, Nexans and KIT started a pilot project, also referred to as "AmpaCity", with the objective to install an HTS system in the downtown area of a German city to demonstrate the technology under technical and economical aspects [11].

AMPACITY PROJECT

Due to the innovative character of the AmpaCity project an application for funding was submitted to the German Federal Ministry of Economics and Technology by the consortium consisting of RWE, Nexans and KIT. After being approved by the ministry, the demonstration project started in September 2011.

As for the feasibility study the downtown area of the city Essen was chosen for the installation of the HTS system consisting of a concentric three phase cable and a fault current limiter. The system was introduced as a connection between the medium voltage busses of two substations replacing a conventional high voltage system. The

HTS system is rated for a transmission power of 40 MVA (2310 A) at 10 kV and the route of the installation with a length of approximately 1 km is shown in figure 1. Substation Dellbrügge is located in the downtown area of Essen in close proximity to the main pedestrian shopping street and the main railway station, whereas substation Herkules with an outdoor switchyard is further away from the city center. The superconducting fault current limiter as well as the cooling system were installed in substation Herkules in order to maximize the space reduction in substation Dellbrügge.

Within the AmpaCity project RWE was responsible for the system specification, the location for the field test, and the implementation of the system in the grid. Nexans was in charge of the development, testing and manufacturing of the HTS system consisting of cable and fault current limiter. The HTS system development was supported by Karlsruhe Institute of Technology with characterization and tests of HTS materials as well as the establishment of a simulation model for AC losses of three phase concentric cable systems and a test setup for precise measurements of these losses on short sample cables.

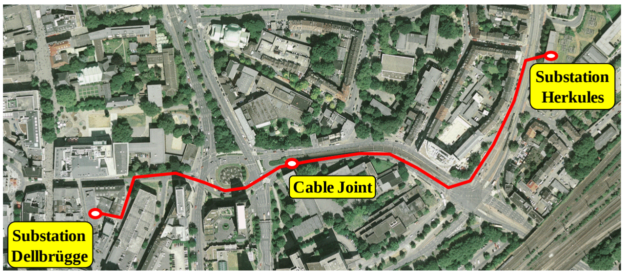

Figure 1 Route of HTS cable installation in Essen [12]

HTS SYSTEM DESIGN

Cable system

The superconductor cable design for the AmpaCity project is presented in figure 2. The cable core is based on a corrugated tube former, which is used as a cooling channel for liquid nitrogen (LN_2). All three phases and a common screen are concentrically arranged around the former, each of them separated by a lapped dielectric of polypropylene laminated paper (PPLP). The three phase layers consist of stranded wires containing HTS material, and the common screen is made of stranded copper wires. The cable core is placed into a cryostat, which is composed of two corrugated tubes in concentric arrangement with vacuum insulation in between. Another cooling channel for liquid nitrogen is provided by the annulus between the cable core and the cryostat. Subcooled liquid nitrogen is circulated through the cable system, keeping the cable core at its operating temperature of below 77 K.

For medium voltage applications, the concentric arrangement of all three phases and the connection in series with a superconducting fault current limiter allows a very compact cable design. Other major benefits of the compact design are the integrated return channel for the cooling medium as well as reduced fault current levels in the downstream grid due to the FCL application. During normal operation the currents in the three concentric phases are balanced, exhibiting the same absolute value at a 120 ° phase shift, and no current flows in the screen. Therefore, no magnetic stray field appears outside the HTS cable system. Additionally, due to active cooling with liquid nitrogen inside the thermal insulating cable cryostat, the system is thermally independent from the environment. This unique thermal behavior and its very high electromagnetic compatibility lead to a simplified siting as well as an easier installation.

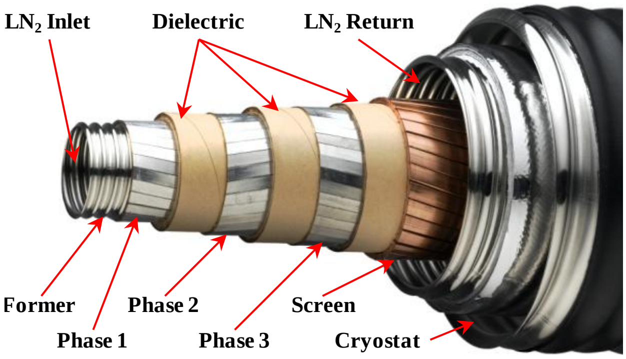

Figure 2 Concentric HTS cable design

Fault current limiter

Superconducting materials exhibit a strongly non-linear voltage-current characteristic. Usual superconductor applications operate below the critical current, where virtually no voltage drop across the superconductor is measured for direct currents. Once the critical current is exceeded, an increasing voltage drop is observed up to the full transition to the normal conducting state. Resistive fault current limiters utilize this transition, during normal operation the amplitude of the alternating current stays below the critical current without voltage drop, and during faults the short circuit currents lead to a high resistance of the device with associated heating of the superconductor. Hence, a fault current limiter introduces a non-linear resistor in the circuit with the transition being triggered by the current. The transition between the superconducting (low impedance) and the normal conducting (high impedance) state is fully reversible. After the limitation the material automatically cools back to its operating temperature. This time interval is typically in the range of a few seconds.

For resistive fault current limiters HTS tapes are typically assembled to limiter components. Several of these components are then connected in series and are assembled into a cryostat which provides the low temperature operating conditions. Three vacuum insulated liquid nitrogen vessels, one for each phase, keep the limiter components stable at the operating temperature of 77 K. A picture of the fault current limiter for AmpaCity is shown in figure 3. The device is designed to limit a 38 kA peak short circuit current to about 10 kA.

Figure 3 Fault current limiter delivered on site in Essen

Cooling system

A cooling system for HTS power applications consists of different components. Most of the systems require forced flow of the coolant, which is provided by a circulation pump. Due to electrical insulation requirements and height differences sub-cooled cryogens are commonly used. Therefore, a pressure regulation system inside the closed cooling circuit is required. The heat input to the circulation system is re-cooled in a heat exchanger. The primary side of the heat exchanger is either cooled by cryocoolers [13] (closed system) or from bulk liquid supply (open system). Vacuum pumps may be applied to the heat exchanger in order to reduce the operating temperature below the atmospheric pressure boiling point of the cooling liquid. An open system features lower complexity and potentially high reliability, but requires refilling of a nitrogen storage tank in regular intervals. After initial filling a closed system only consumes electrical power, but therefore requires higher capital investment and specific methods to ensure availability and reliability. The cooling power of HTS systems is influenced by different factors like system size and total losses. Further, cooling systems do not only have to enable normal operation of HTS systems, but also need to be safe and efficient in all operating modes like cool down and warm up as well as during any failure mode.
The schematic of the cooling system for AmpaCity is shown in figure 4. Due to financial reasons it was decided to utilize an open cooling system with re-filling of a storage tank. The storage tank is installed in a separate section of substation Herkules which can be accessed by the LN_2 truck drivers without utility personnel being present.

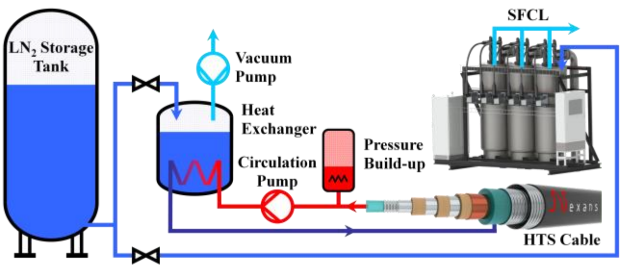

Figure 4 Schematic of cooling system for AmpaCity

PROTOTYPE TEST

The beginning of the project was dedicated to the design phase and specification of the system requirements. In May 2012 a pre-prototype cable was manufactured in order to qualify the manufacturing process and the cable design mainly with respect to high voltage constraints. Since the superconducting material is still quite expensive, only a few HTS tapes were used for each phase layer of the cable and copper tapes exhibiting the same dimensions were used to replace the remaining HTS tapes. All mechanical tests as well as all high voltage tests were successfully completed on the pre-prototype cable. Therefore, the cable design as well as the manufacturing process was validated. Subsequently, in October 2012 a prototype cable was manufactured with each of the phase layers containing only HTS tapes exactly as the cable to be installed in Essen.

Figure 5 Type test setup in Nexans' Hannover laboratory

In the project consortium a type test procedure was designed in agreement with the German standard DIN VDE 0276-620 with respect to the voltages applied during type testing. For the testing basically three different tests with high voltage are mandatory, the partial discharge test, the lightning impulse test, and the AC voltage withstand test. Since two of the dielectrics in the cable separate two different phases, the phase to ground voltage U_0 was replaced with the nominal phase to phase voltage U. For the partial discharge measurements, these modifications lead to a test voltage of 20 kV after previously having raised the voltage to 24 kV for one minute. The lightning impulse test is performed with ten shots of 75 kV for both polarities, and for the AC voltage withstand test a voltage of 30 kV is applied across the different dielectrics. A load cycle test consisting of 20 cycles each lasting 8 hours is also foreseen. During each cycle the cable system carries the design current of 2.3 kA up to 5 hours and carries no current for the rest of the cycle. For type testing the test sequence of partial discharge test, load cycle test, partial discharge test, lightning impulse test and AC voltage withstand test was defined.
The type test of the AmpaCity cable system was performed on a 25 m loop including two prototype cable

sections with cryostats, one joint and two terminations which were set up in Nexans' Hannover laboratory as illustrated in figure 5. All tests of the type test sequence were passed and the complete type test was finished successfully in March 2013. Afterwards manufacturing of the HTS system components for the installation in Essen started promptly.

INSTALLATION

In parallel to manufacturing the system components, the civil works in Essen for the installation of the HTS cable started in April 2013. A polyethylene duct system with an outer diameter of 250 mm and a wall thickness of 12 mm was installed in the ground between each of the two substations and the joint bay. For manufacturing of the cable cryostat it was important to precisely determine the length of the duct system. The joint bay with a width of 2 m, a length of 6 m and a depth of 2.5 m was just accessible during the installation and was backfilled afterwards. The installation of the duct system was completed beginning of September.
The cable cryostat manufacturing was finished once the length of the duct system was determined and the vacuum was pumped for at least two weeks. Before then shipping the two cable lengths to Essen, the cable cores were pulled into the two cryostat sections in the Nexans factory in Hannover. The complete cables were spooled on special transport drums with a flange diameter of 4.2 m and a width of 3.8 m for the bigger drum. At the end of September 2013 the two drums were loaded onto flat bed trucks and shipped to Essen.

Figure 6 Pulling of first cable length from joint bay

The cable pulling was performed by a subcontractor with special equipment to properly handle the drums and the cable. On October 1st, the shorter cable length was pulled from a standard cable drum trailer (figure 6), which was positioned at the joint bay, to substation Dellbrügge. One day later, on October 2nd, the longer cable length was pulled from substation Herkules to the joint bay. The different pulling directions were determined by taking into account the forces on the cables during pulling and the space restrictions on site for the cable drum trailer. The cable cryostat was qualified to support pulling forces equivalent to at least 4 t (4.000 kg) and a sidewall pressure of more than 10 t (10.000 kg).
In the following weeks until the end of November 2013 the terminations and joint of the HTS cable, the fault current limiter, the cooling system as well as all the auxiliary equipment were installed on site in Essen.

COMMISSIONING

After the installation on site was finished, the fault current limiter and the cable system were gradually cooled down to their operating temperature. For the HTS cable the cooling process was achieved within one week while for the FCL the process was performed in two days.
Subsequently, the commissioning test was conducted in December 2013 with a cable test van with very low frequency (VLF) testing equipment at 0.1 Hz. The commissioning tests comprised a partial discharge measurement of each dielectric with 20 kV (figure 7), a loss factor diagnoses with 10 kV, 15 kV and 20 kV as well as an AC voltage withstand test of each dielectric with 30 kV for one hour. All tests with the cable test van were passed successfully.

Figure 7 On site partial discharge measurement

On March 10th, 2014 the HTS system was finally connected to the grid. At first it was only connected to the bus bar in substation Herkules and afterwards to the bus bar in substation Dellbrügge as well. Since then the system is in operation and supplying power to substation Dellbrügge. In steady state operation of the HTS system the required power for the cooling and control system is in the range of 160 kWh per day and the daily nitrogen consumption is about 2 t (2000 kg).

CONCLUSIONS

The application of concentric medium voltage HTS systems enables very attractive grid concepts for urban area power supply. From the current perspective expanding grids using HTS cables is the only technically and economically appropriate option for avoiding the expansion of inner city power grids using high voltage cables, and

reducing the number of high voltage transformer substations in downtown areas. Further, concentric HTS cable systems for medium voltage applications are very compact, exhibit a very high electromagnetic compatibility, and are thermally independent from the environment. For these systems the required right of way is much smaller and the installation is easier compared to conventional high voltage cable systems. In combination with superconducting fault current limiters the fault current levels in the downstream grid are reduced in addition, thus increasing the grids operating safety.
The authors are of the opinion that the AmpaCity project in Germany is world’s first in terms of both content and scope. Worldwide the project is the first implementation of an HTS cable in combination with a resistive HTS fault current limiter in a medium voltage grid replacing a conventional high voltage system. In addition, with a length of approximately 1 km, it is the longest superconducting cable system up to date. The type test including two sections of prototype cable, one joint, and two terminations was completed successfully in March 2013. Afterwards, the manufacturing of the HTS system consisting of cable, fault current limiter, and cooling system as well as the civil works in Essen progressed well. Further, the complete installation in Essen started in September and was finished in late November 2013. The commissioning test of the AmpaCity system was performed with a cable test van in December 2013. After complete commissioning of the HTS system in March 2014, a field test period of at least two years is foreseen.
The HTS technology is still rather unknown, since today no large scale demonstration projects have been realized in particular in Europe. The AmpaCity project represents a worldwide unique reference, and therefore could act as a potential catalyst for initiating the expansion of production capacities in the HTS materials, cryogenic systems, and HTS cable technology sectors. When the target innovation objectives are reached, the electricity supply of major population centers requiring high power may be simplified in the mid to long term through partial substitution of high voltage to medium voltage transformer substations by introducing medium voltage HTS systems similar to the AmpaCity system.

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