ABSTRACT

In Munich, the planning and development of the longest superconducting supply cable in an urban distribution grid is currently underway as part of the SuperLink project. This article will briefly introduce the project and explain the background that led to this idea. In addition, the chances that HTS cables offer for electric grid planning and the conversion of urban energy distribution in the context of the energy transition will be discussed.

KEYWORDS:

city grid, distribution, high voltage, superconducting cables

The Munich SuperLink project

Toughening up city distribution grids with high voltage HTS cables

Local consumption-driven energy generation and feed-in require a stable, efficient distribution grid where energy can be demand-oriented redistributed or fed into the transmission grid

1. Introduction

The energy transition will, in all likelihood, lead to increased stress for the distribution grids, especially in large cities. The switch in the heating and transport sectors, as well as in industry, from fossil fuels to electrical energy conversion will increase the "consumption" of electrical energy in conurbations in the future. In this context, the question is whether the existing grids can handle the increasing challenges. Here we will not dive into details, such as the share size of battery-operated electric vehicles and thus the charging volume, but it is simply assumed that the demand for electrical energy in cities will increase significantly and exceed the capacities of the current infrastructure. In this context, the question of what difference superconducting power cables can make in the future grid infrastructure is being investigated.

2. Motivation and background

In the context of the energy transition to achieve carbon neutrality, there is a lot of concern about expanding renewable energy generation. However, the infrastructure for the distribution of electrical energy will also have to be significantly adapted. Here, the main attention is paid to transmission over long distances because generation and consumption centres are often situated far apart. It is often overlooked that the requirements for urban distribution grids will also undergo drastic changes.

In the foreseeable future, fossil fuels will no longer be used in urban areas for heat generation, transport, or commercial manufacturing. Beyond that, the demand for electrical energy, especially in cities, is constantly increasing due to population growth and re-densification, electromobility, IT technology, and air conditioning. In addition, completely new load centres are emerging, and the dynamics and load flow in the grid are changing. The distribution grids that have grown over decades are not designed for this and must be adapted to the new challenges.

To make things worse, there is the ageing cable infrastructure: many cables are now well over 50 years old and are thus approaching the end of their envisaged service life. Also, the technologies used at that time for the discussed voltage level of 110 kV, such as gas-pressurised cables or oil cables, are no longer available or manufactured, so that replacement and repair are becoming increasingly difficult. Today, it is common practice to replace such old cables completely with XLPE cables during upcoming construction measures. This replacement and the associated grid reconstruction affect practically all major German cities. But also, other European, American and, to some extent, Asian metropolises are facing very similar challenges.

Today's distribution grids are not designed to move or pass through large amounts of energy. Urban grids are characterised by tight meshing. At particularly loaded neuralgic routes, bottlenecks have been often eliminated by parallel multiple-cable systems. High-capacity lines with several hundred MVA capacity are not common in the distribution grid so far and are usually implemented at the 400 kV level. Such installations require cable tunnels as they exist in some large metropolises such as London or Berlin. They always represent point-to-point connections with space-consuming substations at the terminations. As a result, these high-voltage cables tend to form a "backbone" structure with few feeding and extraction points. What will be urgently needed in the future are means to deliver large amounts of electrical energy flexibly to many locations within the cities without cutting 10 or more metres wide trenches through urban neighbourhoods or sacrificing space for huge high voltage transformer stations.

In this situation, the availability of industrially produced, high-performance,

HTS cables offer the chance to integrate high-performance connectivity into existing distribution grids, making grid reconfiguration much more flexible

> **Superconductors enable a paradigm shift in electrical engineering since the high transmission capacity can be achieved with “current instead of voltage”**

high-temperature superconductors (HTS) opens up completely new solution options.

3. The value proposition of HTS technology

3.1 Superconductor benefits

When thinking of superconductivity, the first thing that comes to mind is current flow without losses and higher efficiency. In fact, the loss-free current transport has a much more significant but indirect effect: without losses, there is no heating that could limit the current flow. I.e., superconductors exhibit an extremely high current-carrying capacity and energy density compared to normal metallic conductors. In power engineering applications, the power density of HTS-wire is 300 - 400 times higher compared to copper.

Since superconductors have to be cooled - HTS typically with liquid nitrogen to below 77 K (-196 °C) - the advantages are partly put into perspective by the cryogenics. With cables, however, in relation to the total cable cross-section, there is still a factor of 5 - 10 improvement in transmission capacity, which is urgently required due to the limited space beneath the city walkways.

In traditional cable technology, the conductor current must be limited for two reasons: firstly, to keep the current induced heat losses and carbon footprint low (both scaling with the square of the current), and secondly, to avoid overheating of the surrounding insulation to prevent damage or even breakdown. Rather the voltage is increased when high power has to be transmitted. The superconductor allows a paradigm shift. Since it can carry very high currents without losses, the voltage can be reduced, i.e. the superconductor enables “current instead of voltage” for power transmission.

Thus, an HTS cable can realise the transmission of very high power even at comparatively lower voltage levels in a very slim cable arrangement. For example, more than 500 MVA can easily be transmitted at 110 kV and thus integrated into existing distribution grid structures.

In cramped urban areas, where space and rights of way are scarce and expensive, this advantage is of paramount importance. Instead of massive cable installations or tunnels, a slim HTS cable can be laid in a comparatively narrow trench. This considerably reduces the expenditure for civil engineering and surface reconstruction. In cities, these factors often account for 70-80 % of the total costs of a cable route.

Beyond the pure costs, however, the significantly lower impact on the surrounding neighbourhood and traffic during the construction phase is also important in densely populated and vibrant city centres. Such interference is minimised by the greatly reduced civil engineering work and shorter construction terms. During operation, there are further environmental advantages in addition to loss savings. Due to the design of the superconducting cable, electromagnetic fields outside the cable can be completely shielded, and the cable does not cause any warming of the surrounding soil. As a consequence, there are no strict specifications on spacings, and HTS cables can be laid closely with other infrastructure, which greatly facilitates routing.

3.2 State of the art and reliability

HTS cables have a long track record. The first grid installation dates back to 2001, when NKT operated three HTS cable sections in a grid coupling in a substation in Copenhagen [1]. In the meantime, a whole series of demonstrations have taken place worldwide where HTS cables have been used in the grid to deliver power to customers, e.g. in the USA, Korea, Japan, or China, to name just a few. A good overview of the HTS cable technology and special features of its use can be found in [2].

The longest cable in continuous operation to date is the AmpaCity cable in the city centre of Essen [3]. There, a 10 kV HTS cable replaces a conventional 110 kV cable line, thus saving a transformer station in the city centre. The AmpaCity installation was commissioned in 2014 and had been running smoothly and without interruption in the RWE grid ever since.

A study commissioned by the Munich municipal utility (SWM) before the start of the SuperLink project has evaluated all these cable projects and came to the conclusion that HTS technology is well manageable and proven to be reliable. Hence, the final assessment was that the advantages and perspectives for the conversion of their grid clearly outweigh the risks and imponderables of the new technology.

3.3 Hurdles

However, as with the use of any new technology, there are hurdles to overcome in the beginning. Especially since HTS cables are significantly different from normal XLPE insulated electrical cables, each HTS cable is essentially a pipeline for liquid nitrogen with internal electrics. After laying, a cooling system remains that must be operated and maintained. Typical maintenance periods are 12-18 months for mechanical pumps and compressors, while the uninterrupted service life of Turbo Brayton coolers is specified with 30-40,000 hours.

> **The benefits of HTS cable connections and the facilitation of the distribution grid conversion clearly outweigh the risks and uncertainties that the new technology entails**

This is naturally easier for municipal utilities that operate a broad spectrum of infrastructure (electricity, gas, water, etc.) than for pure electricity grid operators. In order to lower this entry threshold, for the SuperLink project, an industrial consortium has come together for the first time to cover all technical aspects related to HTS cable technology and which can also guarantee long-term service and support.

Beyond the reliability concerns, novel technologies competing against long-established solutions have to address the cost issue. In the early stages, a one-off manufactured equipment competes with high-volume, industrially manufactured, and cost-optimised standard solutions. Since the public grid sector is also subject to state regulation, the cost aspect plays a decisive role in this market. In this respect, cost analysis in the run-up to the project also delivered encouraging results [4]. In fact, the higher capital investment costs for HTS cables are over-compensated in urban areas by the savings in laying and surface reconstruction. The operating expenses, mainly caused by the cooling system, have to be set against the savings of electrical losses. At full load, the HTS cable line can save up to two-thirds of the losses, and at reasonable capacity utilisation (> 50 %) the operation of the HTS line is always cheaper and more efficient than normal cables with comparable power rating. In any case, when analysing costs, the impact on the overall distribution system has to be taken into account.

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4. The SuperLink project

The SuperLink project will specifically investigate how the load centre in the south of the Bavarian capital can be connected to the main feed of the transmission grid in the north by means of a 12 km long HTS cable. The target is to transmit an electrical power of 500 MVA at the 110 kV voltage level via a single, slim HTS cable. Ideally, the cable will fit into partially existing empty conduits with a diameter of 150 mm, which would reduce laying costs additionally.

Besides the city utility, Stadtwerke München (SWM), the project consortium consists of the cable manufacturer NKT, the cryotechnology experts from Linde, the HTS wire manufacturer THEVA, as well as the University of Applied Sciences South Westphalia and the Karlsruhe Institute of Technology (KIT). The project is funded by the German Federal Ministry of Economic Affairs (BMWi) and started in October 2020.

In the 30 months of the project term, the partners are planning to work out a detailed concept for this worldwide longest HTS cable route, develop all the necessary components, perform type-testing and set up and operate a test installation in the SWM grid for half a year. After a successful test, the entire cable line will be put out to tender.

4.1 Concept for a long HTS cable line

Although high-voltage HTS cables have already been demonstrated elsewhere, e.g. the Long Island Power Authority's (LIPA) 154 kV HTS cable [2], the slim design and especially the long length over 12 km pose considerable new technical challenges. The longest HTS cable lines realised so far are around 1 km and could be cooled from one end. For this purpose, supercooled liquid nitrogen circulates in the cable as a refrigerant. In the LIPA project, a closed cooling system was employed, in which nitrogen was recooled by a cryocooler station. The AmpaCity cable, on the other hand, is operated with open cooling, in which nitrogen is refilled from a storage tank and evaporated. The tank must be refilled at regular intervals (1-2 weeks).

Due to its length, only a closed cooling concept is considered for the cable route in Munich, as storage tanks, which would have to be filled very frequently, are out of

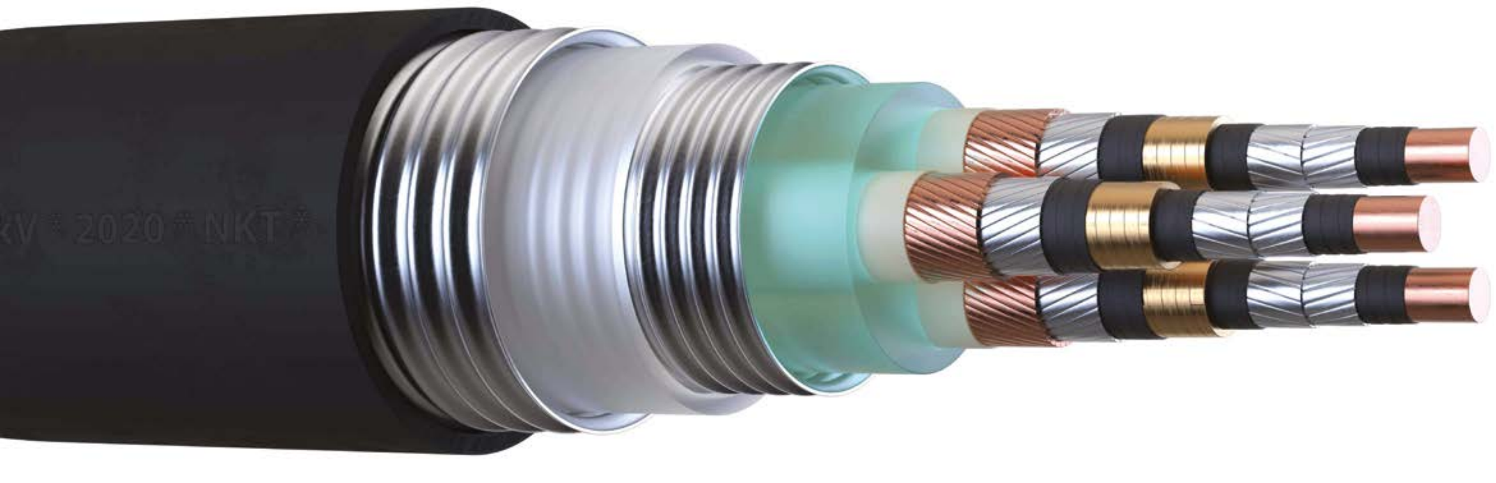

Figure 1. SuperLink HTS cable design (courtesy of NKT)

High-performance superconductors will play a similarly important role in power distribution as broadband optical fibre does in communications

the question. Furthermore, intermediate cooling and pumping stations are needed, as the maximum distance that can be supplied from one side is approx. 4-6 km long. Therefore, an innovative modular cooling concept has to be developed that can be adapted to any length by cascading.

High demands are also made on the cable in terms of compactness and cost. Since the cable cryostat, which consists of vacuum-insulated, double-walled corrugated tubes, represents a significant cost factor, all three phases in the high-voltage cable are accommodated in a single cryostat for the first time. The cable design is exemplarily shown in Fig. 1.

The flexible cryostat is formed by two outer corrugated tubes. The space in between is evacuated and contains spacers and super insulation foil as a radiation shield. Each phase consists of a copper former on which several layers of HTS tape conductor are wound. The less than 0.5 mm thin superconductor layer carries more than 3000 A of current in each phase. Towards the outside, there is a dielectric as high-voltage insulation and another layer of HTS tape serving as a neutral shield. The phases arranged in a triangle are immersed in the flowing liquid nitrogen refrigerant (transparent green). At that point, it is also worth noting that liquid nitrogen is an excellent electrical insulator with a dielectric breakdown strength close to that of transformer oil. Due to the constant nitrogen flow and cryogenic temperature, thermally induced chemical processes are practically halted, and there is no ageing of the components.

Beyond the mere cable, compact joints and terminations and intermediate pumping stations for increasing the pressure in the nitrogen will be developed and tested. The goal is to design a modular HTS cable solution with standardised intermediate cooling stations that are adaptable to various application scenarios and line lengths by cascading.

For the type tests, the same electrical standards will be applied as for any other conventional equipment in the high-voltage range. Transient processes and short-circuit situations are simulated at KIT, and the results will be reflected in the design. Ageing phenomena and partial discharge investigations on the cryogenic high-voltage insulation are carried out at the University of Applied Sciences South Westphalia. Eventually, all components will be set up in a test loop in an SWM substation and operated and monitored under service conditions to gain initial practical operation experience.

4.2 The HTS wire

The HTS wire, which is used for the current-carrying phase and in the shield, naturally plays a prominent role for an HTS cable. It is produced as a so-called coated

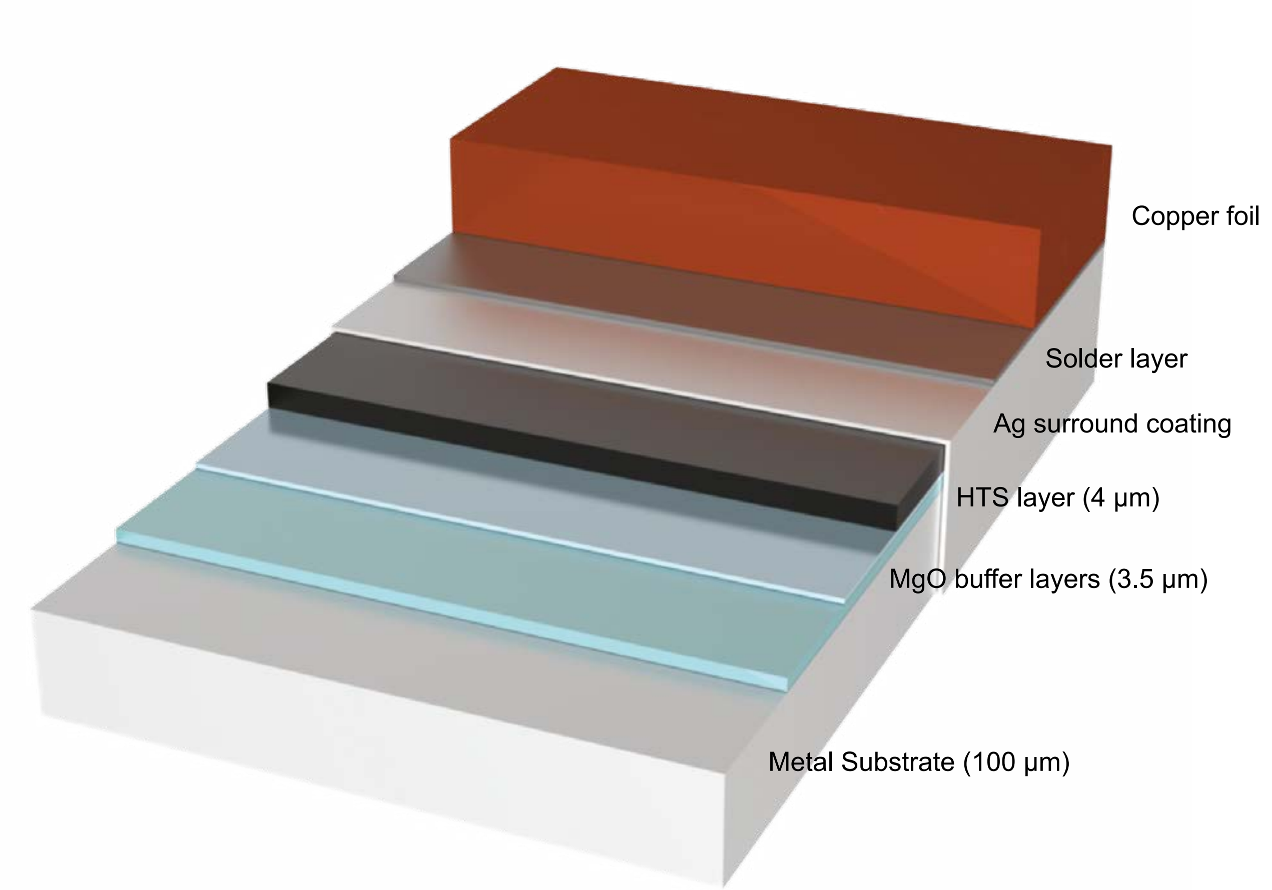

Figure 2. HTS coated conductor design (not to scale, THEVA)

conductor in which thin metal-oxide ceramic layers - buffer and HTS - are deposited on a flexible metal tape (thickness 100 µm). The entire current is carried by the approx. 4 µm thin HTS layer. The conductor is electrically stabilised by a laminated copper foil. The schematic structure is sketched in Fig. 2.

For the application in the cable, there are special boundary conditions and requirements that must be addressed. For example, the conductor should provide ultimate current-carrying capacity, and at the same time, it should be flexible to fit the former, but also mechanically very robust, as it is processed on conventional industrial equipment. In order to avoid immediate burn-out in the event of an overload, electrical stabilisation and safe excess current redistribution have to be implemented. Since the conductor currently accounts for about two-thirds of the cable costs or 30-40 % of the total costs and is thus the largest cost factor, optimising the production costs is a central target of THEVA. From the manufacturer's point of view, strict quality management and the reduction of rejects in the manufacturing process are crucial to ensuring that the project will not only be a technical but also an economic success.

Since the largest cost share of the HTS wire is in the production processes and not in the raw material, there are also straightforward concepts to reduce these costs by upscaling. It is encouraging that a cost level of 50 €/kAm (which currently corresponds to the performance price of copper) can be already achieved by producing the HTS material volume for the 12 km cable and that this opens up other sensible business cases like the one in Munich.

5. Outlook

The authors are convinced that the SuperLink project and the subsequent installation of a 12 km HTS cable through the centre of Munich will spark the widespread use of HTS cables in urban distribution grids, as other city utilities are already watching the Munich initiative very closely.

With superconducting cables, high power can be flexibly transferred at distribution grid voltage so that such connections can be easily integrated into the existing grids. This development may result in the conversion of the entire distribution grid structure - away from tight meshing to a ring structure with high-performance spur lines in which electrical power can be circulated without excessive losses and can be delivered to any location where it is needed. In such a structure, new outlets and feeders can be added flexibly. In addition, many old cable connections become redundant when the grid is converted. In Munich, SWM expects that up to one-third of all high-voltage cables and the associated losses can be saved.

This underlines how important it is to take a systemic view when evaluating HTS technology, taking into account all cost factors and the future perspective that the technology offers. With increasing deployment and installed cable length, cost degression mechanisms are set in motion quite naturally. Costs falling with volume will gradually open up less obvious application scenarios for HTS cables.

New materials are game-changers enabling disruptive concepts and solutions. What has long since taken place in other industries, such as lightweight construction in automobile and aircraft design, or glass fibres in communication technology, is yet to come in the field of electrical power engineering. High-temperature superconductors are currently emerging as smart, innovative, and economical alternatives to copper and aluminium.

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