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Superconducting Electric Lines

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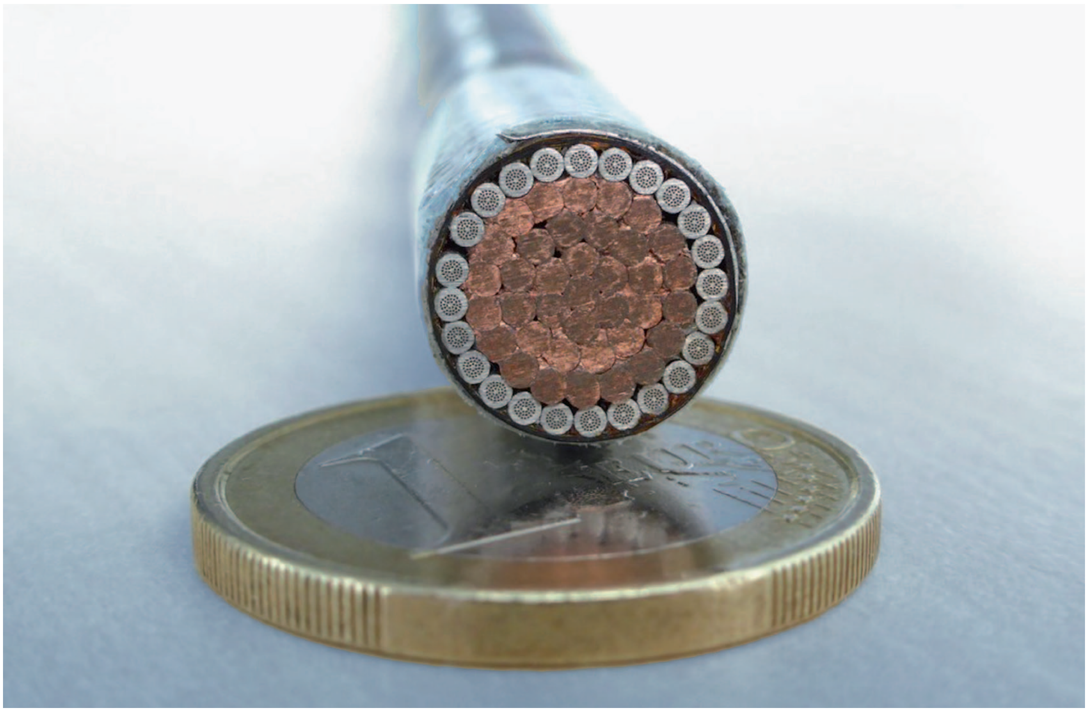
In order to accommodate future demands on electricity grids, including increasing amounts of renewable energy, the current electricity grids will have to be modernised and expanded to enhance their flexibility and add new short- and long-distance links. The limitations of standard transmission technologies have spurred research and development in the field of electricity transmission based on superconducting materials. Although still in their infancy, superconducting power lines might represent a promising option with potential advantages in terms of efficiency, environmental impact and public acceptance.



Source: RTE – Frédéric Lesur

Photo of a superconducting cable composed of 24 MgB_2 wires and a copper core, and with a diameter of only 11 mm. Such cables can carry currents of 10 kA and more.

What is superconductivity?

Superconductivity or absolutely perfect conductivity occurs in materials that display zero electrical resistance when cooled below a characteristic temperature. Contrary to normal conductors, this means that the electric power flowing through a superconducting wire does not incur any resistive losses, making transmission more efficient. The superconducting effect is triggered by very low temperatures, which are specific to each material and range from almost 0 to 130 kelvin (-273 to -143° C).

This phenomenon was first discovered in 1911 when mercury was shown to be superconductive at 4.2 kelvin. Since then, other superconducting materials have been discovered and many technological applications have been developed. Nowadays, superconductivity plays a role, for instance, in medical imaging devices (MRI), generators and particle accelerators.

What are superconducting electric lines?

In the last two decades, research has focussed on the application of superconductivity to large-scale electricity transmission. Developments in this field have been driven by the discovery from 1986 onwards of 'high temperature superconductors', i.e. materials with comparatively high transition temperatures (70 kelvin and greater). This makes it easier and cheaper to reach and maintain the superconducting state, for instance using liquid nitrogen as a coolant.

In practice, a superconducting (SC) electric line would consist of a superconducting cable housed in a cryostat, i.e. a cooling device, and installed underground in a similar way to conventional underground cables. For long-distance connections, cryogenic stations would have to be placed along the line at intervals of tens or even hundreds of kilometres, depending on the design. This is comparable to the distance between compressor stations for natural gas pipelines.

SC lines are expected to have a number of advantages over traditional power lines, not least greater efficiency due to the lack of resistive losses. They are also likely to bring benefits in terms of size, environmental impact and public acceptance. A few pilot projects are already under way and many others are planned (see last section).

The energy transition and the role of the electricity grid

In the coming decades, the deployment of renewable energy sources (RES) such as wind and solar will play a major role in reducing our reliance on fossil fuels and making our energy system more sustainable. But unlocking the potential of renewable energy will require the modernisation and expansion of the current power grids. In particular, grid upgrades are needed to increase the system's flexibility with a view to accommodating rising shares of naturally intermittent renewable electricity. In Europe, the construction of new cross-border links has become a strategic objective that can foster market integration and system balancing. Moreover, the places where RES are available or would be most efficient are often located far away from the densely populated and industrial areas where the energy is required. So there is a need for new long-distance power lines.

At present, the main technological options are High-Voltage Direct-Current (HVDC) overhead lines and, in some cases, HVDC underground cables. Both have a number of drawbacks: overhead lines require massive, intrusive electric pylons and are therefore ill-suited to densely populated areas, while underground cables are extremely costly. Furthermore, both of these conventional options are based on normal conductors and are therefore prone to electrical losses that increase with the length of the line.

In Germany, up to 3 800 kilometres of new lines are expected to be installed by 2024, including 2 400 kilometres of long-distance HVDC north-south 'electricity highways' with a total capacity of 12 GW (*Netzentwicklungsplan*). The latter would correspond to a 6% expansion of the existing ultra-high-voltage grid. While these numbers are still uncertain (and debated), it seems that grid extensions are unavoidable. However, the plans for these new power lines have often been met with strong opposition from local communities due to concerns over their environmental and visual impact, falling property prices and the health risks posed by electromagnetic fields.

What are the characteristics and advantages of superconducting electric lines?

One of the main advantages of superconducting electric lines is the absence of resistive losses, which in the case of conventional technologies range from 2 to 5% for overhead lines and can be as high as 8% for underground cables (per 1 000 km at full load). Fewer losses would translate into increased profitability and less wasted energy.

In comparison to overhead lines, underground cables (both standard and superconducting) have a number of advantages:

- Minimised visual impact on the landscape due to their location underground

- Lower exposure of the surrounding area to electromagnetic radiation

- Smaller ecological footprint (except for wetlands)

- Reduced land use, with less impact on the value of local property

- No effect from most natural weather phenomena such as wind, fog, snow and ice

- No emission of noise.

Moreover, superconducting cables also offer benefits that standard HVDC underground cables do not. First of all, SC cables have a much higher current density, meaning that for a given transmission capacity the total cable diameter can be smaller than for standard HVDC cables. The latter also generate significant heat, which limits their maximum ampacity (ampere capacity) and makes additional cables necessary, thereby increasing the overall size of the construction. By contrast, SC cables are not affected by heat dissipation.

In short, large amounts of electric energy can be transmitted using superconducting cables with very small total diameters including the cryostat. As a result, the whole installation for a superconducting cable can be much more compact than a conventional underground cable with the same capacity. Thus the environmental impact of SC cables can be significantly smaller.

The advantages of superconducting cables over standard HVDC cables can be summarised as follows:

- No heat leakage into the surrounding soil, which is currently one of the arguments against the widespread use of standard underground cables

- Smaller overall size for the same transmission capacity, leading to:

  - Lower impact on soil
  - The possibility of using existing corridors
  - Lower impact on nature, especially in forested or pristine areas (due to the narrower corridor required)

- SC cables can transmit high currents, yet their voltage levels are flexible and can be tailored for optimal performance. Lower voltages translate into simplified electrical insulation, and this can mean fewer transformer stations when the voltage of adjacent grids is matched.

However, the further development of superconducting lines faces a number of specific challenges. In particular, the need to combine two technologies – electricity transmission and cryogenics – introduces a new complexity into the system. Certain issues remain unresolved, such as the choice of appropriate coolants below 70 K and the cost of high-temperature superconducting wire. This might hinder the adoption of SC lines.

What is the current status of superconducting electric lines?

In the last fifteen years, a number of projects involving superconducting transmission have emerged, prompted in particular by developments in the field of high-temperature superconductors (HTS). Some outstanding examples include:

AmpaCity project, Essen, Germany
In early 2014, a 1-kilometre-long underground AC superconducting cable was installed in the city centre of Essen. It replaced a number of aging conventional high-voltage cables and became Europe's first – and the world's longest – in-grid superconducting cable. The cable is designed for a transmission power of 40 MW (i.e. five times more than a copper cable of the same size) and operates at medium voltage (10 kV

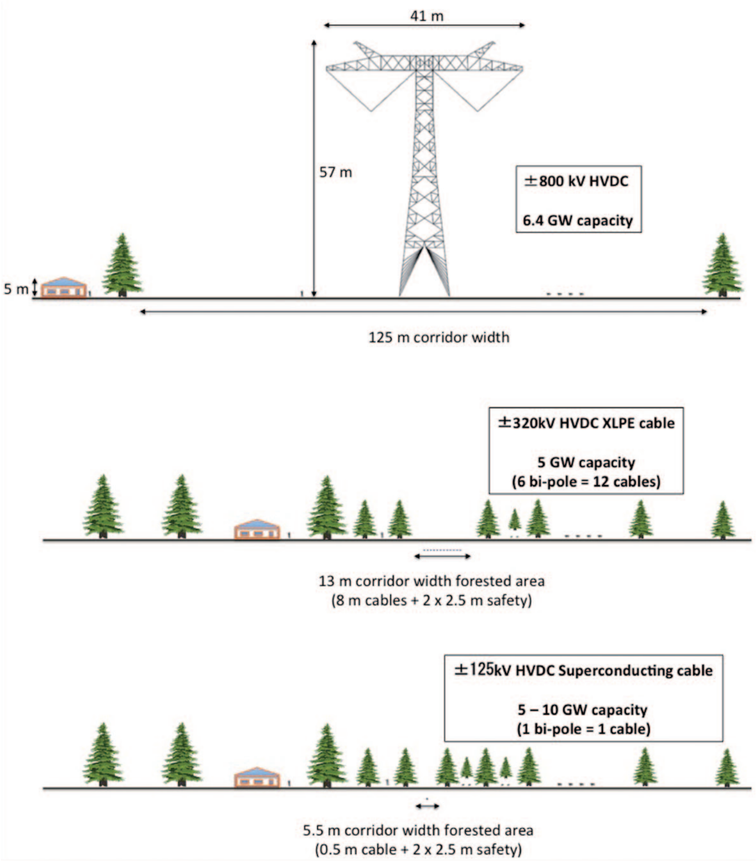
instead of 110 kV), doing away with the need for voltage transformer stations. Overall, the installation of such superconducting links in inner-city areas would free up valuable space and can lead to greater efficiency and lower operating costs. The *AmpaCity* cable is based on high-temperature ceramic superconducting materials and is cooled using liquid nitrogen.

Long Island Power Authority (LIPA), New York, USA
In 2008, a 600-metre-long underground superconducting cable with a capacity of 574 MW was installed to connect a power substation to the overhead line network. Based on high-temperature superconductors, the LIPA cable was the world's longest in-grid cable for the next six years. Currently, the second phase of the LIPA project is running with the aim of making further technical improvements.

Other cables of various lengths and capacities have been deployed or are under construction in Southeast Asia (e.g. Japan, Korea and China) and more recently also in Russia.

Magnesium diboride SC cables
In recent years, research efforts have been directed at exploring the potential of SC lines based on the superconducting material magnesium diboride (MgB_2). After the discovery of its superconducting properties in 2001, MgB_2 was shown to have many characteristics that support its application in electricity transmission:

- It's a simple binary compound, based on raw materials that are abundant in nature.
- It's easy and inexpensive to produce.
- It can be readily manufactured into wires at commercial level.
- It's cheaper than any existing HTS superconductors.



Size comparison of different technological options for electricity transmission.

Source: IASS/ Heiko Thomas

High-temperature superconductors may operate in temperature ranges higher than that of magnesium diboride (thus reducing the costs of cryogenic insulation), but they are more expensive to produce and cannot be manufactured into flexible wires, which is an important aspect to consider for transmission lines.

The European Organization for Nuclear Research (CERN) has been carrying out a series of experiments on MgB_2 wires and cables (as part of a project in cooperation with the IASS) since 2012. Successful tests were conducted on a configuration consisting of two very thin, 20-metre-long MgB_2 cables combined in series for direct current (DC) transmission and placed inside a semi-flexible cryostat supplied with helium gas. This experiment was the first of its kind in the world. The cable set-up, which has a total outer diameter of only 16 cm, was able to transfer a current of 20 000 amperes – a world record for a superconducting cable. These results represent a significant breakthrough and indicate that MgB_2 SC lines are a promising option for the electricity grid of the future.

Recently, almost 40 leading European organisations from science and industry have joined forces with utilities and transmission system operators in the context of a large EU-funded research project on energy transmission. In one of the project's five demonstration areas, a prototype MgB_2 cable will be built and tested in Hannover, Germany. The first components will be assembled in early 2016, and the first tests on the cable system are due to begin in 2017. The cable is intended to comply with recommended industrial norms and will undergo measurements at grid voltage levels much higher than in previous laboratory experiments.

Finally, first estimates of costs conducted by the IASS – which are based on extrapolations from the prototype cable, material costs, etc. – show that MgB_2 cables may be several times cheaper than standard HVDC cables and could compete with HVDC overhead lines. The assessment of the economic aspects of this technology will become more accurate as it progresses from laboratory to industrial scale.

SUMMARY AND OUTLOOK

- For many countries, expanding the electricity grid is a strategic challenge, especially since it relates to energy transition policies and the need to better integrate renewables.

- The standard technological options have a number of drawbacks arising from resistive losses, visual and environmental impact (e.g. electricity pylons), size, and cost (for standard underground cables).

- Superconducting electric lines represent an alternative that exploits the phenomenon of superconductivity to transmit large amounts of electricity without losses. They can be used in short-, medium- and long-distance connections and would be installed underground.

- SC lines can be more efficient and, given their much smaller size, they also have a smaller environmental impact. This increases the likelihood of public acceptance.

- R&D in this field has increased in the past decade, and the viability of SC lines has been demonstrated in several small- to medium-scale projects in different countries.

- However, greater efforts will be required if this technology is to be adopted on a wider scale. The next steps in the development of SC lines include larger in-grid projects as well as work to address outstanding challenges pertaining to the cooling system and the cryogenic stations.

IASS POTSDAM

Institute for Advanced Sustainability Studies Potsdam (IASS) e. V.
Founded in 2009, the IASS is an international, interdisciplinary hybrid between a research institute and a think tank, located in Potsdam, Germany. The publicly funded institute promotes research and dialogue between science, politics, and society on developing pathways to global sustainability. The IASS focuses on topics such as sustainability governance and economics, new technologies for energy production and resource utilisation, and earth system challenges such as climate change, air pollution, and soil management.

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