

Superconductors for the medium-voltage grid

A superconducting power cable running through the inner city of Essen passes a two-year field test



Scientists are testing the longest high-temperature superconducting cable in the world under real conditions in Essen. One kilometre long, it connects two substations in the inner city. It replaces a conventional 110 kV line and renders one substation in the inner city obsolete. After two years of testing, it has passed the field test. It could be a blueprint for the future power supply system in urban areas.

Demand for electricity in these areas is growing. At the same time, Germany's power generation structure is shifting away from large power stations towards a large number of decentralised producers. The grid, originally conceived as a one-way street, has to adapt to these developments: electricity from power stations reaches consumers via high-voltage, medium-voltage and low-voltage grids. For some time now, renewable energy sources, however, have been feeding into the medium-voltage grid. This is why many researchers agree that the energy transition is taking place in the medium-voltage grid.

In particular in the Ruhr area, these new challenges are superimposed by a structural change in the form of a sharp decline in the heavy industry. Here, the changing requirements to capacity and spatial distribution of the grids present special opportunities to test new grid structures and technologies. In the pilot project AmpaCity, scientists from innogy SE and their project partners are investigating how high-temperature superconducting cables (HTS) could be used to banish transformer substations and high-voltage cables from inner cities. As an additional new component of the medium-voltage grid, they employ a superconducting fault current limiter that protects the HTS cable during short circuits. The test helps to estimate the application potential of these superconducting components and to better evaluate economic aspects.

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In over two and a half years of operation, the superconducting system in the city of Essen has shown that the technology is now on the threshold of market maturity. The superconducting cable and the superconducting fault current limiter installed for short-circuit protection work reliably. The technology can be used, for example, in inner city areas in place of expensive high-voltage components, thereby making distribution grids more efficient and economical.

Current instead of voltage

In conventional power supply, cables with copper or aluminium conductors carry the current into the city centres at high voltages in order to minimise transmission losses. Here, large substations lower the voltage to 10,000 volts and feed electricity into the distribution grid. Smaller stations then transform the supply voltage for customers to 400 volts.

With compact superconducting cables, this structure can be simplified. This was confirmed in a feasibility study conducted by the Karlsruhe Institute of Technology, which preceded the pilot project. High-voltage lines and substations could be dismantled step by step by using the new cables in inner city areas, since HTS cables carry large amounts of current over long distances at 10,000 volts, almost without energy losses. Theoretically, high-capacity transmission at the medium-voltage level would also be possible using copper cables, but the energy losses and the demand for transmission routes would be far higher. In Essen, for example, five parallel copper cables would have to be laid underground instead of just one HTS cable.

The conclusion of preliminary investigations is that superconducting cables are the only sensible way to avoid inner city high-voltage cables and to lower the number of resource and area-consuming substations. For a 40-year service life, their economic efficiency versus conventional high-voltage cables ought to be higher as well – despite cooling costs. This superconductor technology has the potential to considerably lower the overall costs created by the future expansion of the grid.

Cool and slender underground cables

The cable connecting the two substations is concentric and just 15 cm thick. A flexible, corrugated stainless steel tube forms the centre axis as a pre-flow line for the liquid nitrogen that cools the cable. It is surrounded by superconductors for three current phases, each separated by insulating layers. Behind one additional insulation layer, a copper shielding functions as the neutral conductor. The entire structure is protected against heat input by the backflow of nitrogen. A double-walled evacuated and corrugated stainless steel tube, the so-called cryostat, serves as an outer „thermos jug“ for the superconducting cable. In the interspace, a film layer metallised with aluminium that serves as an additional super-insulation further reduces incoming heat radiation. A polyethylene sheath protects the cable.

Although the superconducting cable can transmit about five times more current than a conventional 10,000-volt cable with the same diameter, it exhibits practically no electrical transmission losses. This also means that soil drying due to heat losses is prevented. Since HTS cables do not generate magnetic fields, they

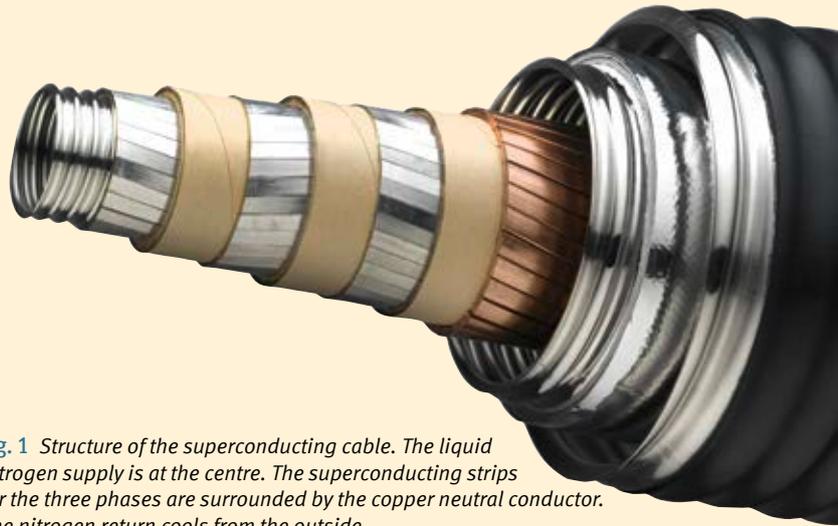


Fig. 1 Structure of the superconducting cable. The liquid nitrogen supply is at the centre. The superconducting strips for the three phases are surrounded by the copper neutral conductor. The nitrogen return cools from the outside.



Fig. 2 Laying the superconducting cable in the inner city of Essen

can easily be installed in already existing cable ducts and can be operated in close proximity to sensitive data cables.

In the technical centre

The technical centre is located in the Herkules substation, where a cryotank supplies the cable with liquid nitrogen. A U-bend at the end of the line compensates for length changes of the superconducting cable when it is being cooled. The short-circuit current limiter is also installed here. It prevents the cable from heating up as a result of short circuits. Otherwise, it would take several hours to cool the cable enough to render it operable again.

The fault current limiter also uses superconductors

The superconducting fault current limiter modules for the three phases of the power grid are connected in series with the superconducting cable. Their AC resistors are extremely small in superconducting normal operation, so they do not influence the flow of current. However, quenching occurs when the current density exceeds a material-dependent threshold value. Superconductivity collapses and an electrical resistance builds up within milliseconds. The short-circuit current is thus automatically limited. The fault current limiter works completely independently and is intrinsically safe. While the superconducting cable uses strips of first-generation material (BISCCO), the short-circuit current limiter operates using

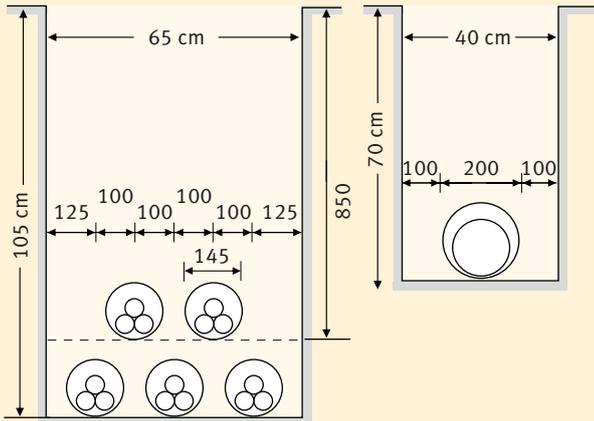


Fig. 3 A superconducting cable requires much less space compared with conventional cables with the same transmission capacity.



Fig. 4 The fault current limiters for the three phases are located in separate cryogenic containers.

high-temperature superconductors of the second generation. They consist of a few micrometers thin layer of superconducting material (yttrium-barium-copper oxide, called YBCO) that is applied to metal strips. The low thermal capacity of the thin strips permits fast cooling. This is why the fault current limiter automatically returns to normal operation after a short cooling phase without requiring further maintenance. The cables and the fault current limiters are dimensioned for an operating current of 2,310 amperes, a rated voltage of 10,000 volts and a rated power of 40 megawatts. They replace a 110-kV cable system with the same capacity.

Cooling with nitrogen

The cable specifications require a nitrogen feed temperature of minus 206 °C at the cable inlet. The liquefied gas then warms up to minus 201 °C by the time it reaches the cable outlet. A subcooler cools it back to the required inlet temperature via a heat exchanger.

The subcooler supplied by the cold specialists Messer consists of a cryostat filled with liquid nitrogen. Vacuum pumps generate a negative pressure inside, which increases the evaporation rate. Evaporative cooling cools the nitrogen to minus 209 °C.

Experiences gained during test operation

After extensive testing and measurements, the superconducting system was officially put into operation at the end of April 2014.

The technicians had to overcome a number of challenges during its first weeks of operation. One of them was voltage symmetry, since the superconducting cable is concentric – in contrast to conventional copper cables. Due to the isolated 10-kV grid, the voltages of the three conductors in the cable differed initially, so the cable was disconnected from the grid by protection devices. By installing capacitors, the required voltage symmetry could be established and the cable was integrated into the grid.

On Whit Monday in 2014, a storm caused a short interruption in the Herkules substation, resulting in an automatic shutdown of the circulating pumps in the cooling circuit. In order to avoid such shutdowns in the future as far as possible, the sensitivity of the control system was reduced.

Short-circuit and earth-fault tests

Since no short-circuit event had occurred in this grid area since the commissioning of the superconducting system until June 2015, the responsible grid operators Westnetz carried out short-circuit tests under real operating conditions in the summer of that year. The cable was isolated from the grid and operated without a load. In four tests with single, double and triple pole short-circuits, the HTS system proved that it could handle practically relevant short-circuits without any damages. „The HTS system mastered not only undisturbed continuous operation but also relevant operating situations in fault operation in actual grid application,“ project manager Dr Frank Merschel explained. Due to its protection function, the superconducting fault current limiter limits the duration of the short circuit to a maximum of 150 ms. All tested short-circuit scenarios were safely managed by the system. The protection systems exhibited flawless responses and functionality, so that no damages to the HTS system or other primary or secondary components occurred.

Outlook

By now, the superconducting cable has been operating without major issues for 34 months and has already transmitted more than 200 million kilowatt-hours. In the category of environmentally friendly technologies, the project was awarded the German Innovation Prize for Climate and the Environment 2015 (IKU). Due to positive experiences made in Essen, superconducting solutions are receiving broad international interest, especially by distribution grid operators, but also industry grid operators.

The system will be used to further the development of the technology following the official two-year trial period. This would include component optimisations as well as measurements of the system.



Superconductors for grids and industry

The power supply system in Germany is changing. Several large power stations are being replaced by a network of comparatively small electricity generation systems. New high-voltage lines transmit wind power from the north to the south on a large scale. Diverse energy storage systems help smooth out the volatile power supply produced by renewable energy sources. The medium-voltage grid for the regional balancing of supply and demand is becoming more closely linked together. With the new structures, higher short-circuit capacities can develop within the grids. Since advanced high-temperature superconductors allow for simple and cost-effective cooling, superconducting equipment greatly extends the toolbox for the new grid. They can render the construction of new lines and plants superfluous, or lower costs. Superconducting cables could reinforce the medium-voltage grid in urban conurbations.

Since advanced high-temperature superconductors allow for simple and cost-effective cooling, they are being used in a growing number of industrial application areas. For example, an induction heater with superconducting components had already been tested in the metal industry ten years ago. Scientists are developing superconducting busbars to electrolyse chlorine, zinc, aluminium and hydrogen. They can replace massive high-current busbars made of aluminium and copper. This eliminates heat emissions, strong external magnetic fields and the high occupational safety requirements of conventional high-current busbars.

Precisely guided superconducting magnetic bearings run without contact and can be designed for extreme loads and speeds. With these properties, they are suitable, for example, for the construction of highly efficient flywheel energy storage systems for more stable grids. With superconductors, motors can be made smaller, lighter and more efficient than conventional electric motors. As industry drives, they achieve five-fold higher acceleration values and allow for extremely rapid speed changes and maximum torques. In shipbuilding, where space is scarce and expensive, the more compact design makes for more efficient space utilisation concepts.

Project participants

- » **Project management:** RWE Deutschland AG (now: innogy SE), Essen, Dr Frank Merschel, frank.merschel@innogy.com
- » **HTS cable and fault current limiter:** Nexans Deutschland GmbH, Hanover
- » **Scientific monitoring:** Karlsruhe Institute of Technology (KIT) – Institute for Technical Physics, Eggenstein-Leopoldshafen

Links and literature (in German)

- » www.innogy.com
- » www.itep.kit.edu
- » www.nexans.de
- » Merschel, F.: Verbundvorhaben: Ampacity – 10 kV-Supraleiter für Hochenergiestrassen. Teilvorhaben: Implementierung und technische Evaluation des Kabelsystems. Schlussbericht Teil I + II. FKZ 03ET1055A. RWE Deutschland AG (RWE), Essen (Hrsg.). Febr. 2016

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