NEXANS SUPERCONDUCTORS FOR ELECTRICITY GRIDS

WHITE PAPER
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ELECTRIFY THE FUTURE

Introduction

The future is electric. From transport to heating, almost everything that currently depends on fossil fuels will need to switch to electricity if zero carbon goals are to be achieved.

This has massive implications for the way that electricity is generated. But equally significant is the impact it will have on the way that electricity is transmitted and distributed.

First, grids will need to be upgraded to enable an expected 60% increase in electricity demand over the next 20 years. This means adapting power networks to cater for new sources of consumption – including electric vehicles, heat pumps, electric heating and industrial processes – as well as accommodating power flows from distributed generation.

Second – and of equal importance – is the need to boost the resilience of electricity supplies. In an all-electric future, fossil fuels will no longer provide a fallback. Transmission and distribution grids will need to be more resilient than ever. Downtime is not an option.

Superconducting cable systems have a critical role to play in addressing these challenges. As well as being highly energy efficient and reliable, superconducting systems are less disruptive to install and require much less space than conventional cables and overhead lines. Moreover, their capacity to transmit power is enormous: a single cable can handle more than 3 GW – enough to power a large city.

A key point about superconducting systems is that they can be cheaper to deploy than conventional copper and aluminium cabling – particularly in urban power grids. Savings are achieved through minimal land take and a reduced need for electrical infrastructure such as substations and transformers.

Superconducting cable systems are not just theoretical – they are now a reality. Leading grid operators already rely on superconducting cable systems for resilient, cost-effective electricity distribution.

The purpose of this white paper is to show how transmission and distribution system operators can benefit by integrating superconducting cable systems into their networks.

As well as describing the technology, we highlight a number of different use cases and show how superconducting cable systems can help grid operators – and their customers – to solve problems, boost resilience and capitalise on the opportunities that lie ahead.

What is superconductivity?

Superconductivity is the loss of electrical resistance which takes place in some materials when they are cooled to a low temperature.

This phenomenon – discovered in 1911 – has major implications for the way electricity is transmitted and distributed. By incorporating superconducting wires or tapes into cables, it is possible to create near-perfect electrical conductors. Superconducting cables have extremely low resistance when an AC current is carried and no resistance when the current is DC.

Superconducting cables for electricity transmission are manufactured using materials known as High Temperature Superconductors (HTS). The word “high” in this context is relative to absolute zero. Despite their name, High Temperature Superconductors need to be kept cold (minus 200 degrees centigrade). Cooling is achieved using a cryogenic envelope – a thermally-insulated jacket that surrounds the cable. The coolant used is liquid nitrogen. This is inexpensive, easy to manage and harmless to the environment.

Aside from the absence of electrical resistance – a highly desirable characteristic in its own right – HTS cables have a number of additional qualities that make them attractive for use in electricity networks.

First, HTS cables are capable of carrying extraordinarily high currents – far greater than conventional copper or aluminium cables. This makes it possible to transmit and distribute electricity at much lower voltages.

Second, they can transmit a phenomenal amount of power relative to their size. To put this in context, a single HTS cable with a diameter of 17 cm (about 6½ inches) can transmit 3.2 GW. This is equivalent to the power of three nuclear reactors.

Finally, superconducting cables produce neither heat nor electromagnetic fields, so there is no interference with surrounding power, telecom and pipe networks.

Together, these properties mean that HTS cables are uniquely suited to solving some of the major challenges now facing distribution and transmission system operators, as well as other major electricity users, including transport operators.

How superconductors solve problems

This section considers the key characteristics of HTS cables and outlines use cases for them in distribution and transmission networks. We also answer some commonly asked questions about superconducting cable systems, including how they can save money.

What are the main characteristics of HTS systems?

High-temperature superconducting cables have a number of technical and physical characteristics that make them strong candidates for applications in power grids.

- Minimal land take – rights of way for HTS cables are up to ten times narrower than those for conventional cables and lines. Fewer cables are required and there is no need for space between phases. This reduces the need for permitting, minimises disruption to the public, accelerates deployment and contributes to lower costs.
- Energy savings – superconducting cables are ultra-efficient conductors with zero or near-zero resistance. The power saving achieved in this way is greater than the energy expended to maintain conductors at a low temperature. By contrast, conventional long-distance transmission systems using aluminium and copper conductors experience power losses of around 10%. This amounts to around 180 TWh annually in Europe alone – enough to power three cities.
- Zero heating – superconducting cables do not emit heat, no matter how much power they carry. This has three important benefits. First, it means that HTS cables can be direct-buried in the ground, accelerating project delivery and reducing costs. HTS cables can be buried deeper than conventional ones because heat exhaust is not an issue. Second, the absence of heating effects means that there is no reduction in transmission capacity when other cables are run in proximity. Third, there is no soil drying effect – a key consideration if HTS cables are run alongside conventional cables.
- No need for tunnels – as noted above, HTS cables can be direct-buried. This means that tunnels and pipes for cables are not required – even in high capacity transmission projects. In cases where pipes or tunnels already exist, retrofitting HTS cables in place of conventional cables dramatically increases the transmission capacity of these assets.
- Minimal EMF – HTS cables are fully shielded to prevent the generation of stray electromagnetic fields, minimising effects on surrounding infrastructure and allaying public concerns about EMF.

Opportunities with superconducting systems

Below, we consider five use cases that take advantage of the unique properties of superconducting cable systems.

DISTRIBUTION Boost the capacity and resilience of urban grids

Distribution system operators need cost-effective and non-disruptive ways to upgrade city power supplies.

Grid operators in urban areas face multiple challenges. First, there is a need to increase the capacity of urban grids to meet rising demand for electricity. Second, there is a need to boost resilience and to ensure the availability of power supplies at all times – even if part of the grid is disrupted. Third, there is a need to upgrade ageing infrastructure. All of this needs to be achieved cost-effectively and with minimal disruption.

How can superconductors help?

Superconducting systems address all of these pain points. One of the major benefits of superconducting cables is that they are capable of transmitting an enormous amount of electrical energy in a remarkably narrow corridor – typically only one metre wide. This not only minimises costs, but also reduces the disruption typically caused by civil works. Another benefit is that electricity can be transmitted at medium voltage. This makes it possible to deploy “remote substations” in the urban fringe and to avoid high-voltage transformers in the city centre – a substantial saving (see Section 4, AmpaCity). Meanwhile, superconducting cables boost resilience by making it possible to provide cost-effective interconnections between substations.

TRANSMISSION Enable the energy transition

Decentralised generation increases the need for high-efficiency transmission.

Traditional thermal electricity generation was located near to sources of demand. But today’s wind, solar and hydropower generation assets are typically sited far away from the populations they serve. As renewable generation increases, so do transmission distances. Finding ways to minimise grid losses is a priority.

How can superconductors help?

Superconducting cable systems offer high-efficiency bulk power transmission over long distances, with none of the resistive losses encountered in conventional high-voltage lines and cables. High-voltage DC (HVDC) superconducting cable systems are particularly suited to this application. Nexans has qualified a 320 kV DC superconducting cable for currents of up to 10 kA with a 3.2 GW power transmission capability (see Section 4, “Best Paths”).

TRANSMISSION Protect environmentally sensitive sites

Grid operators are under increasing pressure to minimise the impacts of transmission infrastructure associated with new energy generation assets.

The growth of renewables and the renaissance of nuclear generation means there is an increasing need to deploy additional transmission infrastructure to link new sources of generation with transmission networks.

New generation assets – particularly renewables such as wind and solar – are typically sited in remote locations, which means that extensive deployments of new grid infrastructure are required in previously pristine environments.

How can superconductors help?

The use of HTS cable systems eliminates the need for visually-intrusive overhead line infrastructure. Furthermore, the rights of way required for new HTS cables are extremely narrow – typically, corridors are only a metre wide. Cables are direct-buried, with no need for pipes or tunnels.

TRANSMISSION Optimise urban land use

Undergrounding high-voltage electricity transmission lines has the potential to free-up land in and around cities.

Easement corridors for overhead transmission lines occupy significant areas of land in and around cities. In many cases, these transmission corridors were established nearly a century ago on land that was then predominantly rural. Today, the surrounding land is urban, but the corridors remain.

How can superconductors help?

Undergrounding overhead lines holds out the prospect of releasing land for new commercial and industrial uses. As already noted, the beauty of using HTS cable systems is that the right of way required is extremely narrow – typically around one metre. By contrast, the cable swathe required with conventional copper and aluminium circuits is sometimes more than 60m wide.

TRANSPORT Railway traction power

Maintaining the resilience of passenger and freight operations is a priority for railway infrastructure managers and train operators.

Railways are major electricity users. In Europe, approximately 55% of the rail network is electrified and this portion carries 80% of traffic. Electricity used at the point of consumption by trains – traction power – is provided at a range of voltages, depending on geography. Common voltages include 25kV AC, 15kV AC, 1,500V DC and 750V DC. Reliable electricity supplies are also mission critical for signalling systems, and for station equipment, such as escalators, ventilation and lighting.

How can superconductors help?

Reliance on single points of grid supply increases the risk to railway operations in the event of a failure at an electricity substation. Adding new feeders using conventional cable technology can be disruptive and prohibitively expensive, particularly in cities. HTS cables overcome this problem, making it possible to deploy new feeders in narrow rights of way.

HTS cables can also be used for distribution within the railway network. This makes it possible to transmit power at the railway's native operational voltage – even if this is a relatively low voltage – over long distances and at a high current, reducing the need for substations on railway premises. The small dimensions of HTS cables and the fact that they produce neither heat nor electromagnetic fields means that it is possible to accommodate superconducting cables within narrow trackside corridors.

Six questions about superconducting cable systems

- **Can superconducting cable systems save money?**

Yes. The greatest potential for savings can be found in projects where medium-voltage HTS cables are used as a replacement for either conventional medium voltage or conventional high-voltage cable systems in urban settings. Savings are achieved through reductions in land take, civil works and permitting, and also through a reduced need for HV transformers and substations in city centres.

- **What is the optimal length for HTS cables?**

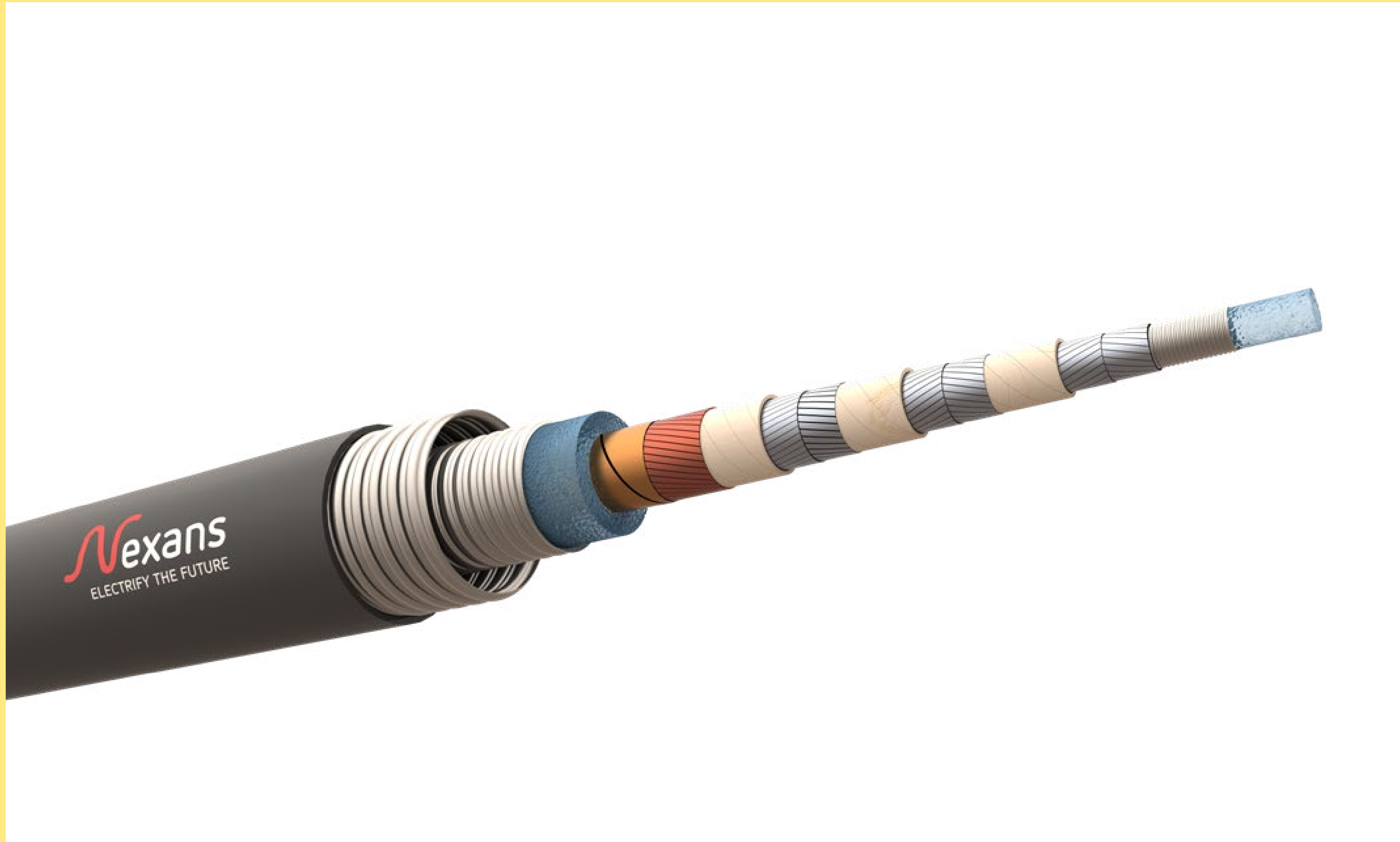
Current HTS projects are between 200m (about 600 feet) and 6km (4 miles). However, there is no technical limit to how long an HTS cable can be. Nexans manufactures superconducting cable in drum lengths of about 500m (1,640 feet) to ease handling on site.

- **Do I need new expertise to manage superconducting cables once installed?**

An HTS cable system is managed in much the same way as a conventional cable system. The only difference is the need to manage the cryogenic system. Cooling is achieved using commercially-available equipment and maintenance is usually provided by the cryogenic system manufacturer while the cable continues to operate.

- **Do HTS cables have any special maintenance requirements?**

Aside from the routine inspection and maintenance of the cooling system, there are no special maintenance requirements associated with HTS cables.



- **How durable are superconducting cables?**

HTS cable systems have been used in grid applications for up to seven years, with complete success. A key point about superconducting cables is that they are less susceptible to ageing than conventional cables. This is because the extremely low temperature within the HTS cable minimises heating, extending the life of insulation within the cable. By contrast, heating is one of the main causes of insulation degradation and ageing in conventional cables. This suggests that the lifespan of HTS cables is likely to be equal to or potentially greater than that of non-HTS cables.

- **What happens if a cable is damaged?**

The coolant used in HTS cable systems is nitrogen, which is chemically inert in both its liquid and gaseous states. It is not harmful to the environment. Although a leak is unlikely because the nitrogen flows in a double stainless steel envelope, monitoring of the oxygen content in the air is required in confined areas.

Case studies

In this section, we consider the drivers behind some real-world deployments of superconducting cable systems and examine the benefits they deliver for grid operators and electricity consumers.

Resilient Electric Grid (REG)

Chicago, USA

Voltage	138 kV AC
Current	2 400 A
Power	600 MVA
In service	2008-2012

The driver: boosting the resilience of power grids is a priority for both policymakers and electricity utilities – particularly in the United States, where energy security is an increasing focus of federal government policy. The Resilient Electric Grid (REG) project in the city of Chicago is part of an initiative by the US Department of Homeland Security (DHS) Science and Technology Directorate to secure America's electricity grid against extreme weather and other catastrophic events.

The solution: the Chicago REG project, which went live in 2022, involved the deployment of a new superconducting cable system to link nearby substations. Nexans designed, manufactured and installed a superconducting cable, which uses high temperature superconducting (HTS) wire made by American Superconductor (AMSC). The cable can operate at 12 kV, has an AC current of 3000 A, and can carry up to 62 MVA of power.

The benefits: the REG system enhances the resilience of the grid, helping to prevent power outages and blackouts by interconnecting and sharing excess energy capacity from nearby substations, and by preventing high fault currents in urban areas. Providing a link of this sort using conventional cabling would not have been feasible. The new 200m HTS cable was delivered in a Commonwealth Edison substation with the objective of installing a 5 km loop connecting downtown Chicago substations in a second stage. The narrow right of way will reduce disruption and mitigate the costs that would otherwise have been incurred through land acquisition and permitting.

AmpaCity project

Essen, Germany

Voltage	10 kV AC
Current	2 300 A
Power	40 MVA
In service	2014

The driver: distribution network operator RWE Deutschland AG was looking for a cost-effective way to serve the city centre of Essen in the west of Germany at distribution voltage. A research project – AmpaCity – was launched to identify the best way to achieve this.

The solution: Nexans worked with RWE, the Karlsruhe Institute of Technology (KIT) and the University of Hanover to evaluate and develop a solution using superconducting cable to link two substations 1 km apart. This was achieved using a single three-phase HTS cable with a capacity of 40 MVA. The new link operated at medium voltage (10 kV) and replaced a conventional high-voltage (110 kV) connection.

The complete solution, including a superconducting fault current limiter (SFCL), was successfully deployed in Essen's grid in 2014. The project was backed by BMWi, Germany's Federal Ministry of Economics and Technology. Nexans manufactured and deployed both the superconducting cable system and superconducting fault current limiter. AmpaCity was the world's longest superconducting cable link and was in operation for seven years.

The benefits: the HTS solution deployed in Essen delivered a number of important benefits above and beyond improving the capacity and resilience of the distribution network.

The right of way required for Essen's single HTS cable was considerably narrower than that which would have been required for either a conventional high-voltage link (which would have needed three single-phase cables) or a conventional medium-voltage link (which would have required 15 single-phase cables). As a result, civil works, permitting and traffic disruption were all kept to a minimum.

A significant benefit of using a medium-voltage (10 kV) HTS solution was that it demonstrated the "remote substation" concept, making it possible, through superconducting cables, to eliminate 110 kV substations in city centres – a significant saving both in terms of space and CAPEX. A TCO (Total Cost of Ownership) comparison for the Essen grid demonstrated that the HTS solution was cheaper than the conventional 110 kV solution thanks to the reduction of the number of transformers and related savings in substation equipment.

Best Paths

HVDC transmission project

Voltage	320 kV DC
Current	10 000 A
Power	3.2 GW
In service	2018

The driver: the EU-funded Best Paths programme was established to identify new ways to integrate power from renewables into Europe's energy mix, including the development of high-capacity transmission networks. One of the key needs in this context is the development of high-voltage DC (HVDC) solutions for bulk power transmission over long distances.

The solution: to test the feasibility of using superconducting cables for long-distance transmission, Nexans designed and built a 320 kV HVDC superconducting loop. This comprises a single 30m cable carrying a current of 10 kA for a rated power transmission capacity of 3.2 GW – enough to power a large city. The programme included a complete sequence of voltage testing at 1.85x the rated voltage (up to 592 kV) and impulse tests. The project culminated in the first-ever qualification on a test platform of a full-scale 320 kV HVDC superconducting loop.

Nexans led the project, with industrial and academic partners including CERN, Columbus Superconductors, ESPCI Paris, IASS Potsdam, Karlsruhe Institute of Technology (KIT), Ricerca sul Sistema Energetico (RSE), Réseau de Transport d'Électricité (RTE), Technische Universität Dresden, and Universidad Politécnica de Madrid (UPM).

The benefits: Nexans' Best Paths solution underlines the vast potential of superconducting HVDC cable systems to meet the need for no-loss transmission of electricity over long distances. The practical benefits of the solution include a modular design that can be easily adapted, making it possible to match the rated current and voltage to any power grid specification. The cable incorporates a magnesium diboride (MgB_2) superconductor, which is relatively inexpensive to manufacture but requires cooling to around minus 250 degrees centigrade. In addition to all of this, land take is minimal: a superconducting dipole carrying 6.4 GW requires a corridor with a width of just 1 metre. By contrast, an equivalent circuit based on conventional copper cables would typically be 10m wide.

LIPA project

Long Island, USA

Voltage	**138 kV AC**
Current	**2 400 A**
Power	**600 MVA**
In service	**2008-2012**

The driver: utilities need ways to overcome grid constraints, while minimising the cost and environmental impact of upgrades. The LIPA project in the US state of New York demonstrated how superconducting cables can address these needs in a high-voltage transmission grid. The project was coordinated by American Superconductor and funded by the US Department of Energy.

The solution: Nexans developed and delivered a complete 138 kV AC superconducting cable system, including the cable core, the cryogenic envelope and the terminations. Nexans was also in charge of supervising cable pulling in ducts and of installing terminations. The host utility was the Long Island Power Authority.

The benefits: the project established the feasibility of using HTS cables in a transmission grid, with benefits that included the ability to carry more power in an existing right of way. The LIPA project established several world records for superconducting cables when it was installed, including longest cable, first in-grid transmission cable system at transmission voltage, and highest power.

Superconducting Fault Current Limiters (SFCLs)

Protecting grid assets with lightning-fast protection from fault currents

Growing demand for electricity and the rise of decentralised generation means that distribution grids are working harder than ever before. One consequence of this is the increasing risk of fault currents caused by short circuits. Fault currents can damage critical assets such as transformers and switchgear. They can also result in power outages, with serious impacts for businesses and consumers.

Superconducting Fault Current Limiters (SFCLs) are designed to tackle these challenges. In normal operation, the SFCL allows current to flow easily and with no losses. But if a fault current should start to flow, the superconductor heats up above its critical temperature and transitions from a perfect conductor to a powerful resistor. The transition takes place in less than 2 milliseconds – about 50 times faster than the blink of an eye. The result is that the fault current is limited immediately. This protects equipment such as transformers, switchgear and busbars on the same circuit.

Unlike fault current limiters that rely on explosive devices to break the circuit, a key advantage of the SFCL is that it does not need to be replaced or reset after use. As soon as the fault current is cleared and the superconductor has cooled down, the SFCL can return to operation. This makes SFCLs the perfect solution for applications where fault currents are frequent, or where access is limited.

Superconducting fault current limiters can be used in any type of distribution grid. These include private power networks for railways and industry. A key point is that SFCLs can be used in conjunction with any type of distribution cabling – not only superconducting cables, but conventional copper and aluminium cables as well.

How can Nexans help?

Nexans is the global leader in the design and manufacture of both superconducting cable systems and superconducting fault current limiters (SFCLs). We provide end-to-end superconducting solutions, from initial concept to deployment and commissioning. And we back this up with expert services and support.

Unique capabilities – our resources include a complete portfolio of technological assets, industrial tools and expertise. HTS cable R&D, engineering, manufacturing and testing are carried out in Hanover in Germany with the support of our plants in France and Norway for some operations. HTS cable accessories and terminations are developed in Calais in France.

Technological leadership – Nexans is the world leader in the field of flexible cryogenic envelope technology – a vital asset for superconducting cable systems. This builds on our decades-long experience in the design and manufacture of insulated flexible lines for the transport of cryogenic fluids.

Superconducting standards – Nexans is playing a key role in the development of new standards through its membership of TC 90, the committee of the International Electrotechnical Commission (IEC) dedicated to the preparation of international standards relating to superconducting materials and devices. Nexans currently chairs the TC 90 committee.

Our unique capabilities in R&D, innovation, testing, manufacturing and deployment mean that we are perfectly placed to assist our customers as they prepare to take advantage of the opportunities offered by superconducting systems.

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